

MODELING AND ANALYSIS
OF
POWER PROCESSING SYSTEMS

FINAL REPORT

Feasibility Investigation
and
Formulation of a Methodology

by J. J. Biess, Y. Yu, R. D. Middlebrook and A. D. Schoenfeld

TRW SYSTEMS

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16. Abstract This report covers a review of future power processing systems planned for the next 20 years, and the state-of-the-art of power processing design modeling and analysis techniques used to optimize power processing systems. A methodology of modeling and analysis of power processing equipment and systems has been formulated to fulfill future tradeoff studies and optimization requirements. Computer techniques were applied to simulate power processor performance and to optimize the design of power processing equipment. A program plan to systematically develop and apply the tools for power processing systems modeling and analysis is presented so that meaningful results can be obtained each year to aid the power processing system engineer and power processing equipment circuit designers in their conceptual and detail design and analysis tasks.					
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1. SUMMARY

The Phase A program covered the feasibility investigation and formulation of a methodology for power processing system modeling and analysis. NASA and military programs planned for the next twenty years were reviewed. The five most complex power processing systems, namely, the Space Shuttle, Sortie Laboratory, Synchronous Direct Broadcast Spacecraft, Solar Electric Propulsion Planetary Spacecraft, and B-1 Military Aircraft, were selected to ascertain that the recommended Modeling and Analysis methodology will be adaptable to the needs of future space programs.

Existing modeling and analysis methodologies were reviewed, and found to be inadequate in all areas, concerning the power processing system weight/efficiency optimization, performance evaluation, reliability assessment, and cost prediction.

A methodology was formulated to facilitate the analysis and modeling of future power processing equipment and systems. The methodology encompasses the following specific concerns:

- Computer-based design and optimization programs capable of performing accurate equipment design and system configuration tradeoff studies for the identification of optimum-weight or optimum-efficiency designs.
- Computer-aided equipment and system performance programs aimed for evaluating all steady-state and transient performances with accuracy, and equally important, with cost-effectiveness.
- A stress-control study program, in support of the reliability analysis tools to be developed, that will ensure the within-rating operation of all power processing components, in magnetic-semiconductor hybrid converters and inverters. The

stress control should be effective during steady-state and, more important, during transient operations, for without this assurance the current, widely-used statistical failure-rate analyses, at best, have only limited validity.

- Cost reductions resulting from the availability and use of the aforementioned design optimization, performance evaluation, and reliability enhancement tools as well as the cost tradeoff study tools to be developed by this program.

Based on the methodology formulated, a six-year plan was conceived for the complete and systematic development of the modeling and analysis techniques and their supporting studies. A detailed program plan for the first year, of the Phase B program, including the work statement, schedule, and the recommended level of effort, is also presented.

The feasibility and the benefits to be derived from this design and analysis technology development program have been established during the Phase A program. The existing technology void, if not filled, will result in preventable penalties in the power processing equipment and system weight/efficiency, performance, reliability and cost.

2. INTRODUCTION

Electric Power Processing Technology is a rather complex field encompassing disciplines of power conversion and control electronics, magnetics, and analog as well as digital signal processing. However, primarily due to the traditional supporting role it serves in relation to other seemingly more glamorous technology areas such as spacecraft attitude control, computer and communication systems, power processing technology development has been hampered by the lack of rigorous design, modeling, analysis, and optimization techniques. Yet, by necessity, electric power processing has been a rapidly evolving technology; the analytical efforts have generally been unable to keep pace with the degree of sophistication already achieved in power-processing circuit development. As a result, heavy reliance on empirical and intuitive methods has become the necessary ingredient in power processing equipment designs. Consequently, the tendency has been for power processing designers to become highly competent in dealing with certain particular circuit approaches rather than to be familiar with: (1) several approaches which could be advantageous for a given application, and (2) analysis and optimization techniques which can be used to identify the optimum approach for a given set of specification requirements. Needless to say, such inadequacies inevitably lead to penalties involving equipment weight, performance, reliability, and cost. In view of the forthcoming needs for use of considerably higher levels of power in future missions, in which brute-force and single-minded power processing techniques would only result in more significant penalties than those of today, the pressing need for a comprehensive power processing modeling and analysis program cannot be overemphasized.

Recognizing such an urgency, a one-year program, NAS3-17782, "Modeling and Analysis of Power Processing Systems," was awarded to TRW by NASA in 1973. The program objective was to investigate

the feasibility in formulating a methodology to systematically develop the needed modeling and analysis techniques. Consequently, the one-year effort represents Phase A of a long-range analysis and modeling program, in which the actual development of the needed modeling and analysis techniques will be executed in Phase B.

The Phase A program was comprised of the following activities:

- (1) The selection of five representative electric power processing systems from those planned for the next two decades, for which the methodology developed in this program can be beneficially applied.
- (2) The identification and documentation of the performance requirements, functional block diagrams, and optimization criteria.
- (3) The surveying and literature search of existing power processing design, modeling, analysis and optimization techniques.
- (4) The formulation of the concepts and methodologies to be used in the development of analysis and optimization techniques for power processing systems and equipment.
- (5) The planning of a detailed program and the proposal for the actual development of the missing mathematical tools, and the experimentation necessary to substantiate the adequacy of the newly developed design, modeling, analysis and optimization techniques.

This report summarizes all the pertinent results obtained during the Phase A feasibility study program.

Since the theme of the Phase A program was the formulation of methodology, Tasks (4) and (5) represent the major output of the Phase A study, with system weight/efficiency, performance, reliability, and cost as the four primary areas of concern. Among the highlights of the study results are:

- The methodology formulation and the identification of a candidate computer technique to implement the overall weight or efficiency optimization of a power processing equipment
- The identification of accurate and cost-effective analytical means to achieve prediction of switching-regulator performance characteristics.
- A discussion of the current weakness in reliability assessment, and the methodology formulation to enhance the reliability analysis and to improve equipment reliability.
- A discussion on how a successful analytical program on optimum weight/efficiency, performance, and reliability can result in minimum equipment cost.
- The formulation of a six-year long-range Phase B program to develop the modeling analysis techniques needed for future aerospace systems.

The results of the five aforementioned Phase A study activities are discussed respectively, in Sections 4 through 8. In addition, a detailed plan for year 1 of the multi-year Phase B program is given in Section 9, which contains the statement of work, the program schedule, and the recommended manpower level.

The major conclusions of the Phase A program are presented in Section 10.

Technical details such as equipment specifications and block diagrams, along with analytical examples including component and circuit design equations, and computer optimization and simulation programs, are reserved for presentation in Section 11, Appendices.

3. TERMINOLOGY

Certain basic terms frequently used in this report are summarized as the following to facilitate terminology clarification.

Power Processing Components (PPC's):

Electronic parts such as magnetics, semiconductors, capacitors, resistors, etc.

Power Processing Functions (PPF's):

An aggregation of PPC's to perform a given duty or operation. Examples include: input filter, power switch drive, etc.

Power Processing Equipment (PPE):

A coherent combination of many PPF's to satisfy certain input/output compatibility. Examples include: line regulator, dc to dc converter, etc.

Power Processing Systems (PPS's):

A combination of many PPE aimed to fulfill the electrical source/load compatibility of a given spacecraft. Examples are: shuttle PPS, sortie lab PPS, etc.

Power Processing System Configurations

The various combinations of the PPE that can be used to satisfy a given system compatibility requirement.

Performance Characteristics

PPS and PPE steady-state and transient behavior that are pertinent to the control, regulation and protection of the load equipment and the PPS or PPE itself.

Design Optimization

To obtain minimum weight or maximum efficiency for a PPS or a PPE.

Computer Simulation

The use of computers to actually portray the microscopic aspects of equipment duty cycle switching.

Computer Analysis

The use of computers to perform calculations based on prescribed equations or expressions.

4. PHASE A SUMMARY REVIEW

TASK 1. POWER PROCESSING SYSTEM (PPS) SELECTION

4.1 INTRODUCTION

The objective of Task 1 was to select a maximum of five most representative aerospace power processing systems (PPS's), for which the modeling and analysis methodology was to be formulated in Phase A in preparation of its complete development in Phase B.

During Task 1 of Phase A there were two PPS selection approaches considered based on: (1) existing and past PPS's, and (2) the PPS's currently in the development and planning stage. Approach #2 was selected as more preferable for the following reasons:

- (1) The five PPS selections represent the different basic PPS types, planned for the next two decades for which the analysis and modeling techniques to be generated by the development program would yield a greater measure of success in achieving maximum payload weight, higher reliability, improved performance and significant cost savings.
- (2) The selection of future PPS's allows the system study to take into account the forthcoming needs for considerably higher levels of power, which impose different component and equipment design constraints than those encountered in the existing PPS's. Identification of new equipment and technology requirements is thus possible, which in turn, allows NASA to prepare the plans for the necessary development programs consistent with overall cost effectiveness.

- (3) The technology in power processing design has been, by necessity, rapidly evolving. The rate of evolution is further enhanced from impetus provided by the introduction of new and improved power switching components. Selections of future PPS's thus allow one to keep pace with the state-of-the-art PPS design, and to be free from obsolete components and designs.
- (4) Past programs generally aimed for weight, efficiency, reliability and performance, with the cost factor occasionally roaming in the background. The obvious trend of increasing sensitivity on future PPS cost, however, certainly would place somewhat different emphasis on the design philosophy and system configuration. These differences can only be adequately reflected in an analysis and modeling program aimed for future applications.

Consequently, despite the fact that existing PPS's tend to provide more readily-available documentation as well as fabricated hardwares for analysis verification, the four overwhelming advantages stated previously have prompted the review of future PPS designs as the preferred approach in the selection of representative PPS's for the modeling and analysis program.

4.2 SELECTION OF THE FIVE POWER PROCESSING SYSTEMS

The selection of the five PPS's was based on the following criteria:

- Systems were selected to include both NASA and military future space flight programs.
- Systems were selected to include all different power sources - fuel cells, solar arrays, batteries, radioactive thermoelectric generators (RTG's), and engine generators.

- Systems were selected to include both dc and ac distributions at a variety of voltages and frequencies.
- Systems were selected to represent future trend of high power demands.
- While cost is a common denominator for all the PPS's selected, other PPS design constraints entered into the selection consideration included reliability, maintainability, and the minimum design and fabrication time allowed for the PPS.

Based on these criteria, the five selected PPS's are:

- (1) The Space Shuttle
- (2) The Synchronous Satellites (including the near-earth orbit satellites similar in design).
- (3) The Planetary Satellite
- (4) The Sortie Laboratory
- (5) The Military Aircraft

A survey of NASA and military future space flight programs, along with concise descriptions of the five specific PPS's selected, can be found in Appendix 11.1.

5. PHASE A. SUMMARY REVIEW
TASK 2. PPS DOCUMENTATION AND TRADEOFF PARAMETERS

5.1 INTRODUCTION

The objective of this task was to lay the technical ground work for Tasks 4 and 5, Formulation of a Methodology, and Phase B Program Plan. The task proceeded orderly through the following sequence:

- (1) Identification of the important ingredients comprising a meaningful PPS documentation.
- (2) Description of PPS configurations and classification of power processing equipment (PPE).
- (3) Interactions of PPE with power sources and loads.
- (4) Documentation of tradeoff parameters for the PPS's.

5.2 IMPORTANT INGREDIENTS OF A MEANINGFUL PPS DOCUMENTATION

The five important ingredients instrumental to a useful PPS documentation, shown in Figure 1, are: (1) program design constraints, (2) spacecraft/aircraft design, (3) power source characteristics, (4) load equipment classification and requirements, and (5) PPE requirements/specifications. Further discussion on these five categories is presented in Appendix 11.2.

5.3 DESCRIPTION OF PPS CONFIGURATIONS AND CLASSIFICATION OF PPE

A PPS encompasses: (1) power source control, (2) energy storage control, (3) source and load power distribution and control, and (4) load power processing. For each of these four categories, there exists a variety of PPE. The nature of the PPE within categories (1), (2) and (4) are similar. Depending on the source/load

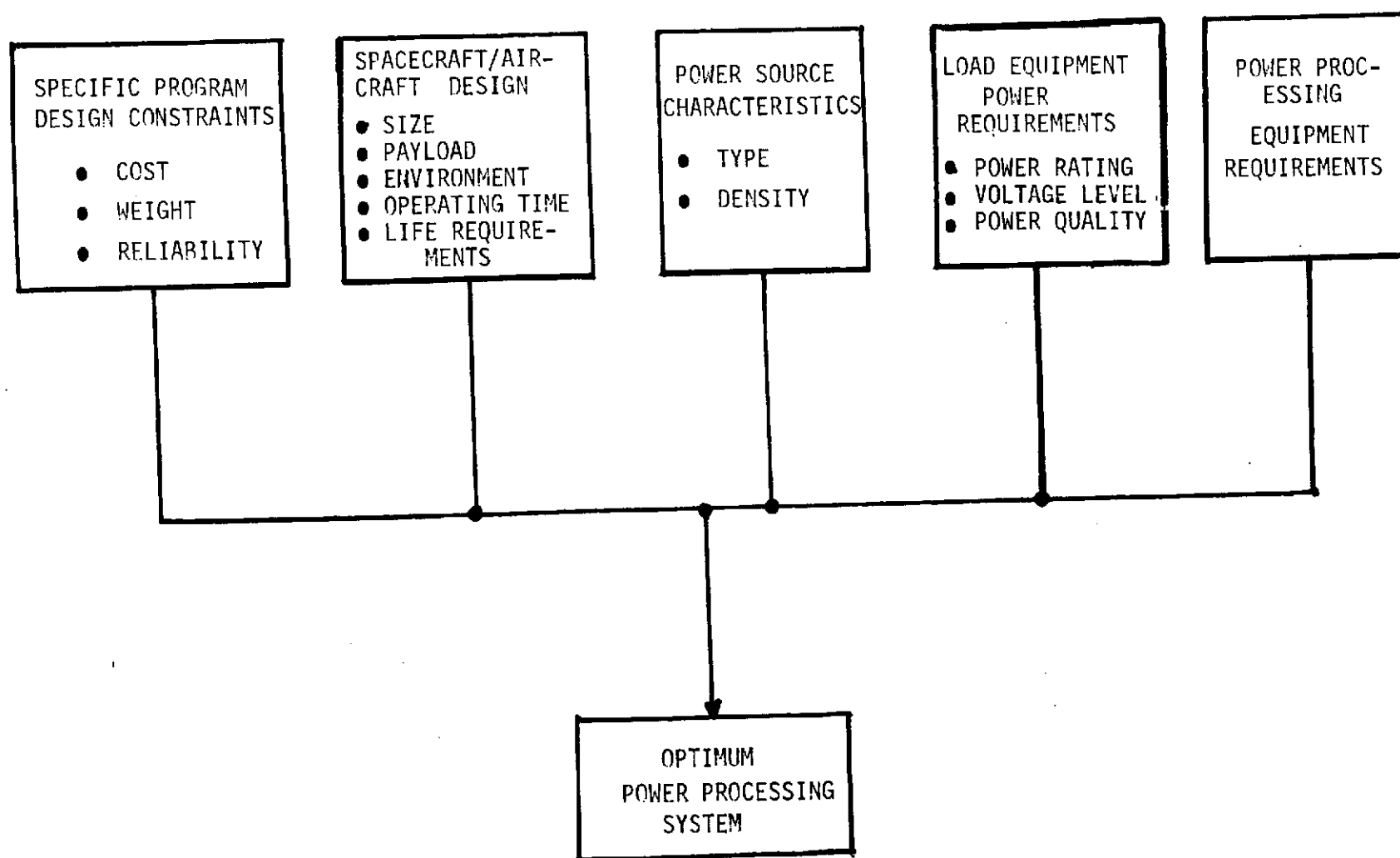


Figure 1. Important Power Processing System Documentation

power distribution types, these PPE can be classified as dc-dc converters, and dc-ac inverters, ac-dc converters, and ac-ac inverters. The fourth category, which includes breakers, fuses, and the feeder cabling, generally finds its way into affecting the PPE design through the impact exerted by power distribution on the PPE requirements and the PPE protection philosophy. Classification of the PPE in this manner identifies the commonality of equipment types among different PPS's, thus potentially reducing the size of the analysis and modeling program through systematic data management of all common PPE.

A system block diagram and a detailed list of PPE classification for all five selected PPS's are presented in Appendix 11.3. For each PPS, the PPE are used in the following load equipment categories: avionic, propulsion, environmental control, power control and distribution, and payload.

5.4 DOCUMENTATION OF INTERACTION AMONG SOURCE/PPE/LOAD

Since the fundamental objective of a PPS is to provide the necessary compatibility between power source characteristics and load requirements, the PPS modeling and analysis cannot be successful unless there is full recognition of the interactions among the source, the PPE within the PPS, and the loads. These interactions exist for all five PPS's selected, and are given in Appendix 11.4.

5.5 PPS TRADEOFF PARAMETERS

Reliability, weight, and efficiency have always been the major tradeoff parameters for past PPS's. In future applications, the cost factor is becoming increasingly important. The expected primary optimization parameter for each selected PPS has been identified and listed in Table 4 of Appendix 11.1.

6. PHASE A. SUMMARY REVIEW
TASK 3. DOCUMENTATION OF EXISTING DESIGN, MODELING AND
ANALYSIS TECHNIQUES

6.1 INTRODUCTION

The objective of this task is to conduct a review of available technical journals, NASA and other government reports regarding the design, analysis, modeling and optimization of PPS's and PPE. It is hoped that through this survey of available engineering tools, those applicable can be utilized in Phase B of the analysis and modeling program.

In general, the survey revealed scant literature concerning PPS analysis and modeling. Although to a lesser extent, there has also been a lack of organized effort to develop rigorous models for all PPE types. These evidences substantiate, at least from the viewpoint of open literature, heavy empirical and intuitive reliances as the basic ingredients in the past and existing PPS development. In view of the forthcoming needs for considerably higher levels of power in future PPS's, in which brute-force design techniques would only result in unbearable weight and cost penalty, the significance of the subject program cannot be over-emphasized.

In contrast to the scarcity of PPS and PPE modeling and analysis effort, rather sophisticated computer techniques do exist. While not developed specifically for PPS or PPE design and analysis, these techniques can, nevertheless, be readily adopted for that purpose once mathematical models and equations are generated to adequately describe the PPE and the PPS.

The survey of existing design, modeling, analysis and computer techniques is documented in the following categories:

- (1) PPS and PPE power circuit design equations and mathematical modeling, with emphasis on weight and efficiency.
- (2) PPE performance analysis to identify equipment steady-state and transient characteristics.
- (3) Available computer techniques to aid the design and analysis of categories (1) and (2).

A summary review for each category is given in the following section. The more detailed documentation is reserved for presentation in the appendices, Section II.

6.2 PPS AND PPE POWER CIRCUIT DESIGN, MODELING AND ANALYSIS

In this category, the key findings on existing modeling and analysis techniques can be divided into: (1) power processing components, (2) power processing functions, (3) power processing equipment, and (4) power processing systems.

6.2.1 Power Processing Components (PPC's)

The PPC's exerting major impacts on PPE reliability and weight are semiconductors and magnetics.

- Semiconductors: Transistor and rectifier steady-state operation models and elaborate computer simulation models are available.^[1] However, deficiencies still exist in the analysis and modeling of transient phenomena, e.g., the transistor second breakdown. Recently advanced models have shown improved qualitative understanding.^[2,3] Continued improvements are necessary for computer-aided reliability analysis.

- Magnetics: Optimum design for inductors and transformers has been attempted, and has been mostly limited to the selection of the minimum-weight magnetic core.^[4,5,6] An improved optimization constraint used is an overall minimum combined weight for (1) the designed magnetics, and (2) the portion of the source (e.g., solar cells) weight necessary to supply the loss in the magnetics. Using the method of Lagrange Multiplier to achieve a closed-form magnetics design, the detailed analysis is presented in Appendix 11.5.

6.2.2 Power Processing Functions (PPF's)

The PPF is defined as the aggregation of a number of PPC's in performing a given circuit function (e.g., an input filter) within a PPE. In an attempt to cover a wide power, voltage and frequency range for various applications, previous PPF analysis has mostly resorted to the "parametric study" approach. An example of parametric data and format of expression generated on a past study program^[7] is presented in Appendix 11.6. Such an approach, while providing certain utility in PPF design, suffers from a serious drawback in practical applications. First, the numerical parametric data, based on available component capabilities and design techniques at the time of the study, easily becomes obsolete with the advent of new components and improved designs. Second, the interdependences among the various PPF's within a given PPE are ignored in the study of separate PPF's.

6.2.3 Power Processing Equipment (PPE)

The PPE is defined as the combination of a number of PPF's in performing a given equipment function (e.g., a line regulator) within a PPS.

While the survey did not reveal any analytical effort to achieve a PPE design specifically optimized for a given design constraint, work was reported in which the overall PPE characteristics such as the PPE weight, loss, and failure rate were obtained from the cumulative effect of the individual PPF parametric data.^[8]

An example of this type of PPE analysis is given in Appendix 11.7, in which the weight, loss and failure rate of a buck-type line regulator are graphically expressed as the accumulation of the corresponding PPF characteristics, using the switching frequency as the independent variable. Such an analytical approach suffers from the same drawback as previously stated for the PPF parametric study, namely, its diminishing utility with the evolving power processing technology. Furthermore, it is handicapped by a basic weakness in that it fails to take into account the close interdependences among the constituent PPF's of the PPE: namely, the impact of selecting a design approach for the implementation of a given PPF is invariably felt by all other PPF's within the given PPE. For example, the input filter can be highly dependent on whether the output filter inductor is designed to operate with a continuous or a discontinuous current. While there has been a lack of optimization effort regarding a complete PPE, well-conceived computer-aided designs and graphics applied to several basic power stages were reported. [9,10]

6.2.4 Power Processing Systems (PPS's)

A PPS is comprised of a number of PPE.

The generation of accurate PPE characteristics regarding weight, loss and reliability has been fundamental to the PPS analysis and modeling. [11] However, the earnest endeavor there was to develop elaborate PPS computer programs rather than accurate PPS and PPE models. No matter what psychological and practical solaces one might derive from these past computer-oriented programs, the fact remains that there is a dearth of readily-applicable PPS modeling and analysis techniques.

6.3 PPE/PPS PERFORMANCE ANALYSIS

Two principal objectives in the analysis of a PPS design are: (1) to determine performance, i.e., output dc regulation, output impedance, line rejection, etc., and (2) to determine

stability against oscillation. To this end, the literature survey has shown that there has been very little attempt at synthesis of the diversified design and analysis approaches. A basic reason for this is perhaps the difficulties inherent in the understanding and analysis of complicated nonlinear control systems.

In the absence of established and well-accepted catalogs of design concept and analysis techniques, works in the power processing field tend to adopt an arbitrary design concept to meet specific requirements, usually, it seems, determined primarily by previous experience and familiarity with the chosen concept rather than by any objective criteria concerning the "optimum" approach. The same is true with regard to choice of analytic techniques. The present status of the field, therefore, is that of a number of conceptual implementations and a number of analytical techniques available, each having been partially developed, but with no comparative information.

6.3.1 PPE Control Circuit Design Implementations

While the number of alternative power circuit types and variations of these types is quite large, there are only two basic classes of control mode:

(1) Duty Cycle Control With a Timing Reference

- Constant T_{on}
- Constant T_{off}
- Constant $T_s = T_{on} + T_{off}$ (clocked, driven)
- Constant $E_i \cdot T_{on}$

(2) Free-running (constant ripple, limit cycle, bang-bang)

The T_{on} and T_{off} refer to the ON and OFF times of the power switch, T_s the switching period, and E_i the input voltage.

These control modes can be implemented through innumerable individual control circuits proposed and in use today. Generally speaking, they can be categorized into two types of control mechanization:

- (1) Single-Loop Feedback Control
- (2) Multiple-Loop Feedback Control

Regardless of the type of control mode or mechanization used, the control system must be able to convert an analog amplified error signal into a related discrete time interval to achieve duty-cycle control of the power switch. This functional relationship can be accomplished through four modulation philosophies:

- (1) Non-integrating explicit
- (2) Non-integrating implicit
- (3) Integrating Explicit
- (4) Integrating Implicit

A more detailed description concerning the control mode, control mechanization, and modulation philosophies, is presented in Appendix 11.8.

6.3.2 PPE Performance Analysis Methods

The PPE performance analysis includes: (1) quasi-linear technique, (2) nonlinear analysis, and (3) computer simulation.

The conceptually simplest quasi-linear technique in past performance and stability analysis is that of the describing function.^[12,13] Here, the accuracy of analytical results deteriorates as the signal frequency approaches the PPE switching frequency. A more complex and less versatile quasi-linear technique employs the Z-transform method of sampled data systems.^[14,15] These methods have been partially successful in analyzing PPE in which the MMF in the output-filter inductor never reaches zero during steady-state operations. The case where the inductor MMF vanishes during part of the switching cycle has, so far, been unsolved.

While the two aforementioned quasi-linear methods are based on frequency-domain characterization, the nonlinear methods are applied directly in the time domain. A well developed technique is the phase-plane method. However, its application in PPE performance and stability analysis has been limited to buck-type line regulators operated in a free-running control mode using a bistable hysteretic tripper.^[16,17,18] Another major area of existing nonlinear analytical effort has been the limit-cycle analysis of switching transients for a family of parallel inverters,^[19,20,21] which provides original and systematic insight into inverter characteristics such as inverter starting and switching spikes.

The third analysis category, computer simulation, has served largely as an adjunct to paper analysis, although recent work has demonstrated the feasibility of a complete PPE computer simulation in place of a solely analytical treatment for performance evaluation.^[22]

A more detailed description concerning the documentation of the PPE performance analysis methods is given in Appendix 11.9.

6.4 REVIEW OF COMPUTER TECHNIQUES

Although not specifically developed for PPE and PPS calculations, all computer programs are readily adaptable for such applications. These programs can be categorized as follows:

6.4.1 Optimization Programs for PPE and PPS Weight, Efficiency, etc.

The basic requirement here is to solve simultaneous nonlinear algebraic equations to obtain a complete PPE (or PPS) design optimized for a given design constraint such as weight, efficiency and reliability.

The Sequential Unconstrained Minimization Technique (SUMT) digital computer program developed by Research Analysis Corporation, McLean, Virginia, was identified as a potential engineering tool.^[23] The identification of this technique was supported by several illustrative examples completed at TRW under Phase A of this program. An example will be described in Section 7, Formulation of a Methodology.

A concise introduction to SUMT is given in Appendix 11.10.

6.4.2 Simulation Programs for PPE and PPS Performance Evaluation

The available computer simulation programs include the following:

- Analog Computer
- Digital Computer Programs:
 - TESS (TRW Engineering System Simulator)
 - CSM/O/P (Continuous Systems Modeling and Optimizing Program - IBM)

The two digital computer programs have equivalent capabilities. An example of TESS application is presented in Section 7 of this report, while that of CSM/O/P can be found in a recent literature.^[22] Further description of these programs is reserved for Appendix 11.10.

6.4.3 General Network Analysis and Computation Programs

The general network analysis programs include the previously-described TESS, the ECAP (Electronic Circuit Analysis Program), the ICAP (a revised version of ECAP), the FORTRAN and the BASIC. Their further descriptions are also summarized in Appendix 11.10.

7. FORMULATION OF METHODOLOGY FOR PHASE B

7.1 INTRODUCTION

The primary objective of this task is to formulate a methodology for modeling and analysis of power processing equipment (PPE) and systems (PPS's) with regard to their efficiency, weight, performance, reliability and cost. The utility of these modeling and analysis techniques is to provide the PPE and PPS designers with engineering tools to analyze and simulate the available tradeoffs in order to arrive at an optimum PPE design consistent with the specified PPE requirement/specification and optimization constraints. By so doing, heavy empirical as well as intuitive reliances need no longer be the prime ingredients in designing the PPE and PPS, and significant improvements in future high power PPE and PPS development can be methodically realized.

The potential benefits, as previously stated, are expected in the general areas of PPS efficiency, weight, reliability, performance and cost. Consequently, a general discussion on the present inadequacy in the areas of PPS and PPE weight, reliability, performance and cost is in order, and is presented in Section 7.2.

Based on the general inadequacies, the needed specific analytical improvements are outlined in Section 7.3.

Guided by these specifics, the necessary groundwork for the methodology formulation is presented in Section 7.4.

Thus, with the problems identified and the foundation of carrying out the approach properly laid, the detailed methodology for PPS modeling and analysis is outlined in Section 7.5.

7.2 PRESENT ANALYTICAL INADEQUACIES IN PPE/PPS WEIGHT, EFFICIENCY, RELIABILITY, PERFORMANCE AND COST

7.2.1 Weight and Efficiency

To anyone designing PPE/PPS, recurrent yearnings for the following analytical tools are evident during his weight and efficiency analyses:

- (1) There is a need for accurate and readily-available power processing component (PPC) data. Power magnetics core losses and semiconductor switching characteristics are two representative examples.
- (2) There is a need for accurate PPE/PPS analytical models that are computer programmed to include all interdependent power processing functions (PPF's) so as to eliminate laborious iterations of various functional designs during PPE/PPS weight-optimization tradeoff studies.
- (3) While the PPE control circuit used to govern the power-circuit operation contributes to only a minor portion of the PPE weight and losses, its impacts on the power-circuit design, in terms of the method of duty-cycle control (i.e., constant on time, off time, frequency, etc.), are not minor. Consequently, the validity of weight and efficiency optimization among different PPE candidate configurations must be supplemented by the analysis of effects of different duty-cycle control methods when applied to each PPE configuration. There has been, however, only scant organized effort in this regard dealing with analysis rather than optimization.^[9,10]

- (4) There is a need for an accurate assessment of the weight impact of PPE packaging, which is itself a function of PPE efficiency, and which contributes to a significant portion of the fabricated PPE weight.

Presently lacking these supports, the state-of-the-art weight and efficiency optimization study preceding the selection of a given PPE (or PPS) configuration has been time-consuming, yet largely without substance, as it is often based on inaccurate data. Most of the time it does not take into account the interdependences among the constituting PPF's within a given PPE. It generally is based on a given control approach familiar to the individual designer, whose knowledge of packaging may be rather superficial.

7.2.2 Reliability

In the field of power processing, perhaps the most lagging aspect at present is that of reliability. It is not unusual that the reliability of an operational equipment fails to achieve the level anticipated from consideration of the reliability of the component devices themselves. Symptoms of a failed PPE too many times include one or more failed components - a manifestation of the fact that the circuit functions performed by these components make them targets for high-energy dissipation during, in most cases, electrical transients. These transients may be generated from the cyclic high-frequency switching operation associated with any magnetic-semiconductor hybrid switching regulator, or they may be consequences of step PPE line and load disturbances including converter starting and sudden output short-circuit. In these regards, it may be on such seemingly minor points as transformer winding techniques, leakage inductance, winding capacitance, magnetics saturation characteristics, etc., that the reliability or satisfactory performance of the PPE hinges. Thus, in the high-power, magnetic-semiconductor, transient-prone PPE, more so than in many other electronic equipment, there is a requirement for a high level of insight on the part of the designers into various effects of the transients. Present effort in this

regard is emerging,^[24] yet gravely insufficient. Failing to attend to the transient operating details, the reliability figure, based on the aggregation of component statistical failure rates, by assuming all PPC's are operating within their respective ratings, has little or no validity.

In spite of this shortcoming, past and existing PPE often achieve the operating reliability through PPE and PPS redundancy, monstrous component derating, and perhaps occasional sheer providence. To sustain these luxuries is becoming increasingly difficult, particularly in view of the high-power ratings of future PPE and PPS's.

7.2.3 Performance Characteristics

Two principal objectives in PPE and PPS performance analyses are to determine (1) static and dynamic output regulation under conditions of steady-state switching operation as well as step or sinusoidal line and load changes, and (2) stability against oscillation. These performance characteristics depend, to a large extent, on the quality of the PPE or PPS control system.

The PPE control system inherently employs many nonlinearities. When faced with analysis of such systems, one has three choices: (1) to extend the linear method in the frequency domain, (2) to treat each nonlinear problem in the time domain on an individual basis, and (3) to use computer analysis and simulation.

The first category, the linearization of the nonlinearity to facilitate the extension of linear methods, can be regarded as obtaining an exact solution to an approximate problem. The entire arsenal of general linear techniques is then applicable. Due to PPE designers' familiarity with linear theories and their preoccupation with frequency-oriented performance characteristics such as audio-susceptibility and output impedance, analysis in the frequency-domain has so far commanded the major effort of PPE and PPS control analysis. However, since the problem is only an approximate one to start with, the solution, even rigorously derived, is incomplete and its range of validity may not easily be defined.

An important example of this subtlety is that the Nyquist stability criterion, while necessary and sufficient for stability of a linear system, is merely necessary but not sufficient in a nonlinear system.

In the second category, each nonlinear analysis problem is essentially unique because known methods of solving nonlinear problems usually have restricted generality. Although exact solutions in terms of given mathematical models can always be obtained by numerical techniques, usually some approximations are involved in order to extract any qualitative generality. Consequently, the second category can be regarded as obtaining an approximate solution to an exact problem. Mainly due to the discreteness of this analysis technique with which the PPE designers suffered from a lack of intimacy, the use of this method in PPE and PPS performance analysis has been extremely rare.^[25] However, the exclusive capability of nonlinear analysis in retaining those properties that may be inevitably lost through the linearization process engaged in the linear analysis has provided the necessary impetus in conducting more nonlinear analysis in the future.

The third category, computer simulation, has often served as an adjunct to paper analysis. This supporting role is expected to continue in the future.

To conduct a PPE or PPS performance analysis that is accurate, complete, and cost-effective, an optimum approach is expected to be based on a time-domain analytical model, in which all nonlinear operating constraints are expressed, in closed mathematical relations, for computer calculation.

7.2.4 Cost

The significance of PPE and PPS cost has been somewhat latent in the past history of space power processing. However, the rising sensitivity to cost has made it a major future design constraint. Due to the past latency, there has been no systematic effort on generating a PPE or PPS cost model. In conjunction with the fact cost often involves such intangibilities as requirement changes, repairability and quality control philosophy, efforts of future cost analysis and optimization, if conducted at the initial stage of the modeling and analysis program when no realistic design requirements and tradeoff programs are available, are likely to be arduous, yet ill-defined and futile. Consequently, analysis and optimization involving cost should be attempted only at the later stage of the Phase B Modeling and Analysis.

Due to the long-term utility of future PPE and PPS's such as those of the Shuttle program, the cost consideration should include not only the initial PPE and PPS design and production (which has been expressed traditionally through the "parts count" involved) but also the maintenance cost and the operating cost.

7.3 SPECIFIC ANALYTICAL IMPROVEMENTS

From the foregoing discussions, specific improvements needed in the PPE and PPS Modeling and Analysis can be listed as the following:

7.3.1 Weight and Efficiency Analysis

- (1) The analysis upgrading must start with improved power processing component (PPC) data, with emphasis placed on the following information:
 - The core loss as a function of switching frequency and flux excursion for various core materials under asymmetrical squarewave excitation.

- The switching loss of the power switches, and the effects of recently-developed energy-recovery networks on the switching loss. [25]
 - The realistic worst-case equivalent series resistance (ESR) of solid and foil tantalum capacitors.
 - The availability status and reliability assessment of high-power Schottky diodes. [26]
- (2) Armed with the correct PPC data, one can then proceed to achieve weight and efficiency optimization for the PPE and PPS. Specific improvements required are the following:
- The mathematical formulation of (1) power processing function (PPF) design based on a given set of PPE input/output requirements and (2) the interactions among the interdependent PPF's such as input filter, power stage modulation, and the output filter.
 - The mathematical formulation to represent different weight and efficiency impacts exerted on the PPE by the implementation of different duty-cycle control methods.
 - The generation of a set of guidelines in determining the weight impact due to PPE packaging as a function of the power capability, the voltage rating, and the operating environment.
 - The elimination of any overspecified PPE requirements to minimize the weight penalty. For example, requiring the input filter of a 10KW switching regulator to meet MIL-STD-461, Notice 1, conducted interference at a 10KHz switching frequency is, needless to say, sheer absurdity.

7.3.2 Reliability

A truly meaningful reliability analysis lies in the complete assurance of limiting the electrical stresses on all PPC's to within their respective ratings during not only the steady-state operation, but more important, during transient operations. Such assurance can be achieved through the following complementary design and analysis approaches:

- State-of-the-art power circuit design including the peak-current limiter,^[26] the energy-recovery network, and in some instances the use of inherently current-limited power inversion stages^[27] would completely bring the operating current in the various PPC's under control.
- The high-frequency models of magnetics (both inductors and transformers) and power semiconductors (to the forward and reverse regions) need to be developed to facilitate a complete magnetics-semiconductor hybrid circuit analysis. The development of these analytical models is likely to be difficult. However, only through such an analysis can the semiconductor dissipation characteristics and voltage spike during switching be quantitatively assured.

Furthermore, it is expected that valuable outgrowth of these models would concern another type of reliability - the starting of a self-oscillating type of parallel inverters. The topic will be discussed further in Section 7.3.3.

7.3.3 Performances

Specific analytical improvements in PPE and PPS performance evaluations can be categorized into four areas. They are: (1) static and dynamic output responses, (2) stability, (3) PPE starting into the desired limit cycle oscillation, and (4) switching pattern and phenomenon.

Static and Dynamic Output Responses

The improvements needed in this area include the following:

- In addition to continuing the frequency-domain linearization analysis techniques described in Section 7.2.3, work must be initiated on the use of the time-domain nonlinear analysis techniques to uncover, if any, the deficiencies associated with the linearization process.
- Select the most applicable analysis technique to develop comparative information for the various control circuits in existence. The information should also include the effect of different methods of duty-cycle control on the PPE performance.
- Identify the "optimum" control approach and recommend standardization of PPE control circuit.
- Formulate the normalized control-circuit design as a function of power circuit design.

Stability

In contrast to the frequency-domain characterization of the quasi-linear methods, the nonlinear discrete time models are applied in the time domain, and emphasis is therefore necessarily placed at or near the switching frequency. Consequently, the nonlinear methods are most useful in examining the stability, and should be pursued vigorously in Phase B.

PPE Starting into the Desired Limit Cycle Oscillation

The starting abnormalities including limit-cycle oscillation at either higher or lower frequencies than those desired, happen frequently in self-oscillating types of converters. Recent work has begun to focus attention on these problems by studying the starting of resistive-loaded inverters. [19,20,21] Additional efforts are needed to extend the study into supplying reactive loads. The study should also include the converters, i.e., with the addition of rectifiers and filters.

Switching Patterns and Phenomena

This area of study, applied to high power magnetic-semiconductor hybrid switching circuits, is virtually non-existing at present, for the simple reason that there has been no established high-frequency equivalent-circuit model for the magnetics or the transistors. However, a thorough understanding here is essential in terms of gaining confidence in the capability of main power switch(s) to withstand the peak energy dissipation during switching. The problem is by no means simple, as the switching is heavily dominated by the stray parameters such as leakage inductances and junction capacitances. Computer simulation of the actual switching circuitries is perhaps a sensible way to gain qualitative understanding, provided that the intrinsic characteristics of the power transistors can be adequately portrayed.

7.3.4 Cost

Being a function of multiple factors, supporting studies are needed to clarify the many intangibles and tradeoff possibilities. One can state at this time that to start with a successful analysis and modeling program leading to a clearly defined, completely automated, optimum PPE and PPS design will certainly be most effective in enhancing the cost reduction of future PPE and PPS's. Later, the modeling and analysis program shall be expanded and refined to tradeoff the overall program cost, the benefits and penalties of component, function, or equipment redundancy versus modularization, built-in test equipment and maintenance, etc.

7.4 GROUNDWORK NEEDED FOR PPE AND PPS MODELING AND ANALYSIS

For the modeling and analysis program to proceed in a systematic and orderly fashion, the assembly of certain basic groundwork is needed. Strictly speaking, this groundwork of information gathering can be considered as part of the methodology formulation. However, in the interest of separating the necessary preliminary support from the actual methodology of modeling and analysis, the supporting work is included in this section, preceding the description of the methodology itself.

The enactment of the groundwork assembling will be accomplished through the following sequence. First, the PPE and PPS under study, their requirements, and their optimization criteria, must be established. Various power processing functions (PPF's) forming the PPE are then classified. The designs of these PPF's are generally interdependent. The requirement specifications and the interdependences, along with critical power processing component (PPC) characteristics, become basic inputs to each PPF. Combinations of these PPF's form a PPE, which, in turn, leads to the formation of a PPS, for which the modeling and analysis methodology will be formulated.

7.4.1 Identification of PPE Requirement Specifications and Their Interactions

The fundamental building block for a PPS is the PPE. To those engaged in PPE tradeoff studies and design optimization, it is apparent that the study effort must start with a set of well-conceived PPE specifications. These requirements dictate design interactions among the internal PPF's of a PPE, and therefore define the design constraints of each individual PPF. With the advent of future high power PPE, realistic requirements are vital in achieving minimum design penalties and PPE incompatibilities. As a matter of fact, part of the utility of the modeling and analysis program output is to be able to vividly expose the severe penalties incurred from unreasonable specifications.

A detailed requirement list including power source characteristics, load characteristics, PPE output power quality, internal control, command, and protection feature, EMI, mechanical and thermal design constraints, and reliability, is presented in Appendix 11.11. Complex as it may seem, each item listed therein is related to the design of at least one specific PPF. In Phase B this list will be thoroughly screened for the selected PPS's, and those key items that have significant impacts to PPE weight and efficiency, reliability, and cost will be identified.

It should also be emphasized that these requirements generally interact among one another. Any misunderstanding in these interactions can either generate penalties in the PPE design or cause the PPE to miss the specified requirements. These interactions are clearly identified in Appendix 11.11.

7.4.2 Identification of PPE Optimization Criteria

While weight and efficiency, reliability, performance, and cost are the four basic concerns of the modeling and analysis program, the performance optimization will more likely be an outgrowth of the control system analysis rather than an influential source dictating its own methodology formulation. Consequently, the discussion of optimization criteria will be limited to weight, efficiency, reliability, and cost.

Weight has been a primary design criterion in many previous NASA programs, as the PPS weight is often limited by the capability of the launch vehicle. This primary position may be diminishing in certain future applications. Since specific improvements concerning weight and efficiency have been presented in Section 7.3.1, it is merely iterated here that the PPS weight/efficiency optimization will be aimed at achieving a minimum PPS combined weight including: (1) all PPE, (2) power source and storage weight penalty due to losses in the various PPE, and (3) the structure weight penalty due to the thermal control requirement.

Reliability optimization usually includes the consideration of (1) the allowable mean time between failures, and (2) no single-point system failure. Its achievement is most sought after in manned and long life missions, where crew safety and lack of maintenance are, respectively the primary concern.

Regarding the PPE/PPS cost optimization, which applies to most future systems, the five cost categories that must be considered are: (1) development, (2) design, (3) production, (4) operation, and (5) maintenance. The most significant development costs will be associated with certain special PPE involving simultaneously high voltage and high power. Most PPE are expected to fall into the category where existing design techniques are available. Both the design cost and the production cost can then be estimated based on the number of parts within the PPE electrical design. The PPS production cost includes the extra power generator and energy storage costs required to supply the losses in the PPE's. The spacecraft operational cost includes the cost of the fuel cell expendables to supply the PPE losses, and the jet fuel to provide the PPE losses in aircraft operations. The maintenance cost as a separate entity is made possible by the future capability of servicing the PPE in space. The cost will be related to the PPE original cost and the failure-rate characteristics.

As stated previously, the PPS optimization effort to-date have been based on inaccurate PPE data. Extensive design time and high cost to meet the PPE and PPS requirements have been prevailing rather than the exception. It is to the minimization of the effort and the cost associated with future NASA and military PPS's that the optimization techniques developed in this modeling and analysis program will be dedicated.

7.4.3 Identification of Basic Power Processing Functions (PPF's)

The PPF's can be grouped into power functions and control functions. The power function is associated with the main power flow from the PPE input to its output, which the control function manages in accordance with certain pre-set references and commands. Of the four

areas of analysis and modeling concerned, weight and efficiency are overwhelmingly related to the power functions and performances to the control functions. Both power and control functions are, however, intimately associated with reliability and cost.

The basic power functions include power modulation, inversion, transformation, rectification, passive filtering, RFI filtering, and power control and fault isolation. The basic signal functions include sensor, reference, analog and digital signal processors, power switch interface, digital logic function, relay driver, and telemetry. Definitions and detailed sub-division of these functions are presented in Appendix 11.12. The classification and definition provide a common terminology among PPE designers, which is a prerequisite for realizing the utility to be provided by this modeling and analysis program.

The PPF's presented are the building blocks for all PPE; the PPE modeling and analysis is based on the detailed mathematical formulation of each PPF. With the fundamental significance of the PPF thus asserted, variations in PPF combinations to form different PPE are discussed next.

7.4.4 Formulation of PPE Block Diagrams

A list containing general types of PPE for both dc and ac PPS's is given in Table 1. The block diagrams, based on different combinations of the PPF's defined previously, are included in Appendix 11.13.

During the course of the Phase B study, special load equipment such as TWT and ion engines will undoubtedly be encountered, which will necessitate the generation of dedicated PPE block diagrams to satisfy individual equipment requirement specifications.

The block diagram establishes the basis for the requirement specification of each PPF. The interdependence among the PPF's, which was mentioned previously in Sections 7.2.1 and 7.3.1, can be intrinsically linked through the defined PPE requirements. This

TABLE 1. POWER PROCESSING EQUIPMENT LIST

DC Line Regulator (Dissipative)
DC Line Regulator (Switching)
DC-DC Converter (Preregulator/Squarewave Inverter)
DC-DC Converter (Pulsewidth/Frequency Modulated Inverter)
DC-DC Converter (Buck/Boost Configuration)
DC-AC Inverter (Step Wave Form)
DC-AC Inverter (High Frequency Pulsewidth Modulator)

AC-DC Converter (Unregulated)
AC-DC Converter Line Frequency Operation (Regulated)
AC-DC Converter - High Frequency Operation (Regulated)
AC-AC Inverter (Cycloconverter)
AC-AC Inverter (DC Link)

Source/Load Power Distribution Unit

Feeder Line

linkage will become clear from a subsequent presentation in Section 7.5. At the present time, the relevance of the interdependence is further illustrated. The interdependence existing among the PPE functional blocks can be defined as the impact felt by other PPF's as a result of the design implementation of a given PPF. Unfortunately, there is a dearth of information leading up to an effective assessment of these interdependences. Consequently, their full impact cannot be made apparent even after the completion of rather laborious quantitative studies, thus incurring PPE cost and other penalties. To illustrate these interdependences, the basic power circuit of a buck-boost switching regulator is used as an example in Appendix 11.14. Design variations for the power modulation functional main inductor in the block is shown to impact directly on the "input and output passive filtering" blocks, thereby extending its influence to the overall PPE.

The analysis and modeling techniques to be developed can be most effective and useful only if they can provide a means of achieving the optimization among all interdependent PPF's. This is considered essential, for without which the utility of the development would be limited to optimization at the functional level, and would have no validity in arriving at an optimum PPE design.

Generally, more than one PPE configuration (i.e., PPF combination) can be used to satisfy a given set of PPE requirements. Quite frequently, definite tradeoff possibilities among candidates require a detailed analysis before an optimum PPE configuration can be identified. For example, a dc-dc converter to achieve voltage transformation and input/output isolation can be done through many variations that include the use of buck-boost inductive-energy storage, quasi-squarewave PWM parallel inverter, line regulator followed by squarewave inverter and others. The formulation of PPE configuration will take all these possibilities into account. Subsequent discussions on the methodology formulation, therefore, should

be understood to include all configurations rather than a singular one arbitrarily chosen. Modeling and analysis techniques will be generated for each configuration, with the objective of design optimization based on a given optimization criterion. The optimized design of the candidate PPE configurations are then compared, from which the optimum PPE design is identified.

7.4.5 Formulation of PPS Block Diagrams

The combination of PPE to form a PPS is illustrated in a generalized PPS block diagram shown in Figure 2., which includes all PPE listed in Table 1.

The main power source feeds the source distribution units and the multiple load feeder lines. Each main feeder line supplies power to the respective load power distribution units and their associated power processor/load combinations.

An uninterrupted power system, including secondary energy source and energy storage, supplies power to critical loads through its own dedicated power distribution unit. Power is supplied either directly to loads using power at unregulated voltages, or with dc-dc converters to loads using regulated dc power, or with dc-ac inverter to loads using regulated ac power.

By generating subroutine computer programs for all blocks within the PPS, including feeder line, source/load distribution units, and all other PPE, Figure 2, can be mechanized into a computer flow diagram for a generalized PPS. Notice the multiplicity of feeder lines, converters, and inverters throughout the system, which lend themselves to the possible use of an identical computer subroutine.

While an optimization subroutine performed for each individual PPE will definitely demonstrate its utility in terms of designing an optimum PPE, it must be realized that such an optimum design only applies to a particular set of PPE input/output requirement specification. Thus, the utility of these subroutines will likely

GENERALIZED POWER PROCESSING SYSTEM **BLOCK DIAGRAM**

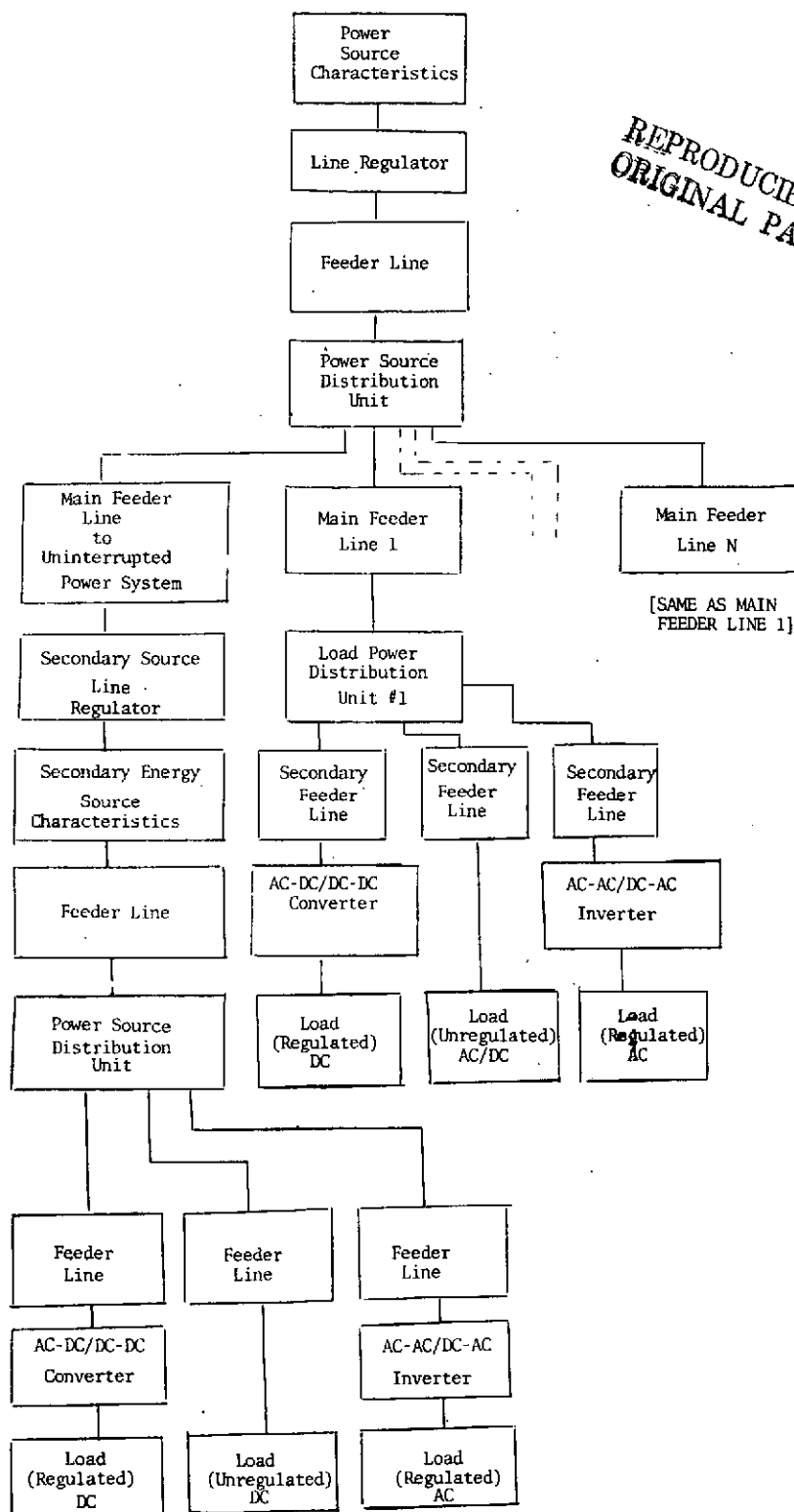


Figure 2. A Generalized PPS Block Diagram

be appreciated, to a considerably different degree, by the PPE designer and the PPS designer.

To a PPE designer who is only responsible for the particular PPE and who receives the equipment specifications already set by the PPS personnel, the individual subroutine would undoubtedly be a complete answer to his earnest request. To him, the application of the computer programs would be convenient and direct.

To the PPS personnel who are entrusted with the selection, among many candidates, of PPS conceptual designs and their configurations, and who must dictate to the PPE designers their detailed PPE input/output specifications, the individual optimization subroutines represent only a partial answer. He must now prepare a list of candidate system configurations, the various PPE for each configuration, and the attendant requirement specifications for each component PPE. Then, using the subroutines as engineering tools, he can subsequently identify the optimum configurations from the PPS perspective, based on his evaluation of system optimization criterion, from which he can proceed to communicate with each PPE designer to carry out the overall system implementation.

To summarize this section, the necessary groundwork for conducting a systematic modeling and analysis program includes the proper identification of: (1) PPE requirements, (2) optimization criterion, (3) the basic PPF blocks, (4) the PPE block diagrams, and (5) the PPS block diagrams. Failure to do so would render the program in a confusing state, with attendant shifts in emphasis and tacit omissions.

7.5 FORMULATION OF METHODOLOGY FOR PPE/PPS MODELING AND ANALYSIS

With all the groundwork properly laid in accordance with the previous description, the methodology formulation of modeling and analysis, by definition, should start with plans to develop models

and equations. Since the power processing components and functions (PPC's and PPF's) are the basic constituents of the PPE/PPS, they should be the initiation topics for PPE/PPS analysis and modeling. While by no means complete and yet to be arranged into a coherent unity, the PPC and PPF modeling and analysis have nevertheless been practiced for most existing PPE/PPS's. The methodology of organizing existing PPC and PPF analyses, and conceiving new analyses, is presented in Sections 7.5.1 and 7.5.2.

As previously stated, from the PPE/PPS weight and efficiency viewpoint, one major weakness of past analyses would be the negligence of the interdependences among various PPF's within the PPE. The primary difficulty responsible for the persistence of this defect has been the lack of identification of suitable computer techniques capable of solving all simultaneous equations representing these interdependences, without which the interdependence-conscious designers were hopelessly handicapped in their attempts to achieve an integrated analysis. The interdependences can be formulated through the specified input/output requirements and the interval PPF design constraints. The formulation, working in unison with a suitable computer program identified in Phase A, will be described in Section 7.5.3.

From the practical viewpoint, the present computer technique of analyzing the PPE/PPS reliability based on the aggregate statistical failure rate of all PPC's is meaningful if and only if, that the respective component ratings are never exceeded during any operation including single-event or recurrent transients. The methodology thus should be tailored to predict and to ensure that the electrical stresses on the PPC's stay within the prescribed limits. This topic is addressed in Section 7.5.4.

The PPE/PPS performance relates closely to the design of both power and control circuits. The vast complexities of a PPS in terms of various PPE nonlinearities and various interactions among the

PPE certainly would discourage a solely analytical treatment with no computer aid. The methodology for performance calculated is given in Section 7.5.5.

The design, development and production cost estimate of a PPE or a PPS is dependent on the technical readiness of the design and development and the parts count as an important gauge. In real life, cost is also a function of such intangibles as program structure, uncontrolled specification changes, the worker personalities, etc., and few of these can be properly modeled and analyzed. Any methodology leading to cost optimization is therefore, by necessity, influenced by subjective judgment. For this reason, the discussion on cost presented in Section 7.5.5 will contain less concrete recommendations than that on weight, reliability and performance.

7.5.1 Formulation of a Methodology for PPC Modeling and Analysis

The major PPC's needed to be addressed to during Phase B of the Modeling and Analysis program are magnetics, semiconductors, and capacitors.

Magnetics

With few exceptions covering specialized high-voltage applications, the overriding preoccupation in most magnetics design aiming for a given set of performance specifications is to achieve either a minimum loss for a given weight, or a minimum weight for a given loss. Immediately, the following concerns can be raised:

- (1) Is there an accurate model for core loss under asymmetrical squarewave excitation, as a function of frequency and flux-density excursion for different core materials?

- (2) Is there a thorough understanding on the eddy current loss in the copper wire caused by flux linkage in the wire, particularly in high frequency, high current operations? Under what conditions are the use of Litz wire mandatory to effect loss reduction?
- (3) Can one determine the adequate amount of "fly-back energy" of a square-loop core that is indispensable in sustaining oscillation in so many timing and drive applications, and yet has so frequently been glossed over in terms of "circuit descriptions"? Questions like these can go on and on, each without a well-conceived and well-documented answer.

Since power magnetics represent a major portion of the total equipment weight and a significant percentage of the total equipment loss whenever switching regulators and input/output filters are used, and since there are still vast unknowns concerning their design and operation (particularly acute in view of the future high power, high frequency PPE), it is recommended that a program dedicated to the magnetics be granted. The program can be expected to fill the present vacuum in certain critical areas of magnetics design which include, among others, the following items of interest:

- To collect, either through analysis, or more effectively through experiment, the pertinent core and copper loss data. The variables there should include core materials, core and coil configurations, including Litz wire, and excitation waveforms, frequencies, and flux excursions.

- To achieve an optimum magnetics design based on closed-form analytical magnetics design solution of simultaneous equations representing various design and optimization constraints so as to eliminate time-consuming iterations. Reduce these solutions in computer programs to facilitate automated optimum magnetics design for dc and ac filter inductors, square-loop core power transformers, and energy-storage inductors.
- To develop an analytical model for high-frequency transformers and inductors to gain better understanding in all switching and incidental transient phenomena, thus enhancing the reliable operation of magnetic-semiconductor hybrid circuits.
- To address certain commonly-encountered power processing phenomena closely related to the magnetics design, such as the use of "flyback energy" to sustain oscillation, the excessive voltage spike in magnetic-semiconductor hybrid circuits, and the "effective inductance" which is smaller than the designed value due to the manifestation of small ac core losses as a resistance shunting the inductor.
- To specify test requirements to adequately assure product repeatability and reliability, and to establish standard methods for magnetics testing in anticipation of the increasing needs of higher power at higher voltage or higher current levels.

With the support of certain previous programs and this program, the task of optimum magnetics design has been initiated. Using the method of Lagrange Multipliers, optimum inductor and transformer weights were obtained by formulating the two constraints: (1) the core window space is essentially filled, and (2) the electromagnetic capacity of the magnetics is fully utilized. From the analytical results obtained, for an inductor, for example, all design parameters including the cross-sectional area, the mean length and the permeability of the core, as well as the number of turns, and the combined core and copper weight are expressed in closed equation form in terms of the inductance desired, the peak current in the inductor, the copper wire size, the saturation flux density, the filling factor, the winding pitch factor, the copper density, and the core density. The analytical detail is presented in Appendix 11-15.

Semiconductors

From strictly the PPC viewpoint, the single semiconductor modeling and analysis concern is the future trend of high power. Accompanied by the adequate protection and derating requirement, the high power demand could conceivably exceed the voltage and/or current capabilities of transistors. Silicon-controlled rectifiers are presently available with single chip (wafer) at ratings of 1000V, 110A rms, and 5 μ s turn-off. They undoubtedly can, with the help of the proper power circuit design, be utilized to their advantages in a great many future high power, high frequency applications. The tools for the weight, reliability, performance and cost tradeoffs between the PPE's using these two types of power switches shall be developed in Phase B of the modeling analysis program.

Since such trade-off studies cannot be divorced from practical circuit designs and tests, it is recommended that circuit development studies be executed separately, yet in close coordination with the Modeling and Analysis program to keep an effective information flow that will benefit both programs.

The power diodes play roles in PPE which are complementary to and as fundamental as those of the transistor or SCR switches. Involving only one p-n junction, the diodes will continue to outpace the power switches in their electrical capabilities. Literatures on paralleling diode operations^[28] and low forward-drop Schottky diodes^[29] are beginning to emerge. Continually keeping abreast of this newly-available information concerning diodes should be sufficient for the purpose of this analysis and modeling program.

Capacitors

Capacitors are important in the analysis and modeling effort due to their impact on: (1) the output ripple caused mostly by the equivalent series resistance (ESR) within the capacitor, (2) the stability of the PPE control system through the capacitance or the ESR change with the ambient temperature, and (3) the damping effect contributed by the ESR to an LC filter, which may have unwittingly prevented many detrimental oscillations in past or existing equipment. These effects will be reflected in the future PPE modeling and analysis.

7.5.2 Formulation of a Methodology for PPF Modeling and Analysis

From PPC to an optimum PPE, one must start with the derivation of the basic mathematical equations transcribing the operation of each PPF within the PPE. The derivation identifies: (1) the PPF

design constraints in order to meet the given PPE requirements, and (2) the electrical ratings of all PPC's within the respective PPF. To illustrate the first identification, a fourth-order, two L-C stage input filter is used as an example in Appendix 11.16, in which the filter design is mathematically described in accordance with a set of given attenuation and resonant peaking specifications. To illustrate the second identification, the rms current in the second-stage capacitor, and therefore the rms current rating required of the capacitor (in conjunction with a prescribed derating factor), is determined in Appendix 11.17 for the buck, buck-boost, and boost dc to dc converter configurations operating with either a constant T_{on} , a constant T_{off} , a constant $E_i T_{on}$, or a constant $T_s = T_{on} + T_{off}$.

While design optimization can be obtained for the individual PPF, it does not mean much as the design of one PPF is often closely related to that of another PPF within the same PPE. Consequently, an optimum design (in terms of weight, for example) for one PPF may cause sufficient weight penalty to another PPF so that the combined PPF does not represent an optimum PPE weight. This interdependence was numerically demonstrated previously in Appendix 11.14, concerning the existing design and analysis inadequacies. The mechanism of interlinking these interdependences through mathematical formulation is discussed next.

7.5.3 PPE/PPS Modeling and Analysis - Weight and Efficiency Optimization

Two distinct steps must be followed to achieve the goal of PPE/PPS weight/efficiency optimization. The first step is the optimization for the PPE; the second step is the optimum configuration of the various PPE to form a PPS.

While, for the first step, the PPS designer may hold discretion on whether he wants weight or efficiency optimization insofar as a particular PPE is concerned, his overriding interest on the PPS supplying a given spacecraft input power, P , is one in which the

total system weight W_{PPS}

$$W_{PPS} = (W_{PPE})_e = (K_{ps} + K_{es})\left(\frac{1}{e} - 1\right) P$$

is a minimum. Here, $(W_{PPE})_e$ is the total weight of all the PPE with a net efficiency e , K_{ps} and K_{es} are power densities (kilograms/watt) associated with power source and energy storage. In other words, the PPS weight, which includes: (a) the total PPE weight, and (b) the incremental solar array and battery weight needed to supply losses in the PPE, is at its minimum.

Repetitive emphasis has been made on harmonizing all interdependences among various PPF's in order to achieve a PPE optimization. The fibers eventually linking these interdependences are the specified PPE input and output requirements. Since all requirements will ultimately find their way into being represented in the detailed equations governing the design of the interdependent PPF's, the interdependences are inherently preserved within the system of simultaneous equations prescribing all PPF's (within the same PPE) and subscribing to a given set of input/output requirements and optimization criterion. Once a computer program can be executed to acquire solutions to these equations, the end results would authentically portray a detailed optimum PPE design, down to component level, in accordance with the optimization criterion specified.

A major effort during Phase I was to identify a computer program that can solve the nonlinear constrained simultaneous algebraic equations with fast convergence. Working in conjunction with TRW Systems' Computer Department, a penalty function algorithm was identified as the engineering tool. Here, each constrained equation is solved as an unconstrained equation and its error determined iteratively to converge to the desired solution. Based on this algorithm, the Sequential Unconstrained Minimization Technique (SUMT) computer program described previously in Appendix 11.10, was

used to solve the nonlinear constrained simultaneous equations. The program is basically a research tool. Depending on the nature of the equations, many internal options can be used to speed up the rate of convergence.

A discussion on the general categories of solving simultaneous equations and the penalty-function algorithms is presented in Appendix 11.18.

Due to the highly original nature of: (1) pioneering the PPE optimization and (2) using a research-oriented computer program, efforts applied to this endeavor could be characterized as both arduous and gratifying. The objective of establishing a methodology was met by demonstrating successfully, in order of ascending degree of complexity, the accomplishment of an optimum-weight design for: (1) a toroidal inductor, (2) a single-stage LC filter, and (3) a two-stage LC filter. The last problem, the most complicated one, contains fifteen variables. In relation to the two-stage filter shown in Figure 3, the fifteen variables are given in Table 2.

Based on a given set of input/output power requirements, a given loss limitation, a given peaking and attenuation specification at a fixed switching frequency, and the weight per microfarad values for both C1 and C2 obtained from known component data, the computer program calculates all fifteen variables, down to the details of the inductor design, in achieving an overall minimum-weight input filter.

A complete report on this and other SUMT applications is given in Appendix 11.19. The presentation here is merely to emphasize the potential utility and benefits of this computer program for future PPE/PPS design.

While time and schedule limitations of the Phase A program did not permit the excursion into a more complicated problem, e.g., a PPE consisting of many interdependent PPF's, it is expected that continued work in the Phase B program will ultimately lead to the automated detail design of future PPE and, to a lesser degree, PPS's. Specifically, further effort in Phase B will include:

Figure 3. Two-Stage Filter Used for Demonstration of Weight Optimization

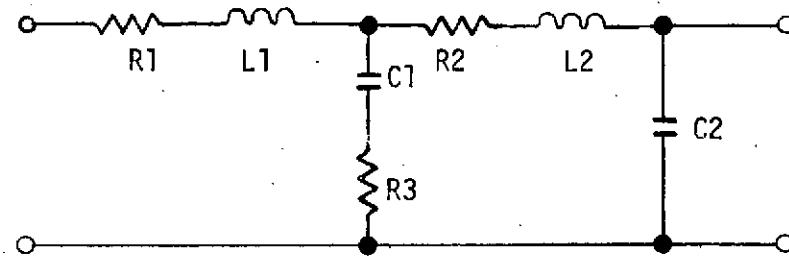


Table 2. Two-Stage Input Filter Design Parameters

Components Variables	L1 *	L2 *	R1	R2	R3	C1	C2
Core Cross Area	X	X					
Number of Turns	X	X					
Wire Size	X	X					
Inductance	X	X					
Length of Core	X	X					
Resistances			X	X	X		
Capacitances						X	X

*Information in this column completely defines the permeability for both L1 and L2.

(1) the application of a SUMT type program to the design of other PPE configurations (such as a line regulator with an input filter) requiring more simultaneous equations, (2) the investigation of internal program option techniques to speed up convergence for accurate solutions, and (3) the implementation and the storage of a component data bank to facilitate actual physical designs.

Work in this direction was initiated in Phase I, during which the mathematical equations specifying the operation of all PPF's within a series switching buck regulator were formulated. These equations include the following design constraints: (1) losses in each power-circuit PPC and PPF including magnetics, semiconductors, and capacitors during normal conduction as well as during switching, (2) input/output filter characteristics such as attenuation, resonant peaking, output ripple, and filter-capacitor rms current ratings, and (3) a filled window and a controlled maximum flux density for each inductor. The equations are ready for SUMT-processing. A presentation of these equations is given in Appendix 11.20, in which the linkage of all interdependent PPF's by the PPE input/output requirements, and the selected optimization criterion is vividly demonstrated.

7.5.4 PPE/PPS Modeling and Analysis - Reliability Enhancement

The accuracy of existing modeling, analysis and prediction of PPE/PPS reliability rests solely on the assumption that all PPC's are operated within their ratings under all circumstances. When this assumption holds, the conclusion on reliability, based on statistical failure rates, can enjoy a high level of confidence. When the assumption fails, however, frequently so does the PPE. In the later case, existing data concerning reliability becomes meaningless, and no amount of elaborate quality assurance or sophisticated reliability analysis can prevent the inevitable consequences.

The key to reliability enhancement, therefore, is a PPE design where all its PPC's are controlled to operate within their respective ratings during all conceivable steady-state conditions, and in particular,

during transient operations. The emphasis on transient-caused consequences is manifested by the concern of the PPE designers with catastrophic degradation component failures.

As a consequence, the means to achieve reliability enhancement is to implement circuit techniques to limit, on an instantaneous basis, the electrical stresses in all PPC's, thus ensuring safe PPC operations during steady-state and transients. While this implementation is instrumental in improving the macroscopic aspects of PPF reliability, one needs to gain better understanding of the microscopic aspects of the failure mechanism caused by either incidental or recurrent transients, from which one can learn to design preventively the transient-prone magnetic-semiconductor switching circuits to mitigate the causes of failures.

Following these two guidelines, the formulation of methodology in reliability enhancement can be outlined as the following: (1) Study of PPE/PPS control philosophy and circuit means to limit the electrical stresses of the PPC's within a PPE under all circumstances. (A certain class of PPE, notable for its reliance on the LC resonance as an integral portion of the power modulation process, can be excluded from the study due to its inherent capability of peak-stress limiting.) (2) Modeling and analysis of the fine microscopic details related to high-energy transients and operating subtleties generated from the switching of magnetic-semiconductor hybrid circuits.

For approach (1), the most effective way of controlling the stresses of PPC's within a PPE is to limit the current in the switching power magnetics. This not only limits the energy storage and saturation current of the magnetics, but more importantly, the limitation is propagated throughout the entire power circuit due to the fact that the MMF in the magnetics cannot change instantaneously. Since the power magnetics for all PPE are connected in series with the main power switch during its conduction time, the best approach

is to turn off the power switch whenever the peak current in it exceeds a certain predetermined level. The implementation of this philosophy requires compatible PPE control concept and control circuitries; the study of these compatibilities will be undertaken during Phase B.

For approach (2), some examples of the general areas of interest will include: (a) the peak-energy dissipation and the voltage spike associated with the power semiconductors during switching transients between conduction and blocking states, (b) the magnetic-semiconductor circuit operation during sudden line and load changes, (c) the distribution of current among the multiple secondary windings of an inductor following the interruption of its primary current (e.g., a buck-boost converter with multiple outputs), and (d) the effect of stray elements and inverter loadings on the starting and operating characteristics of the self-oscillating types of parallel inverters. Unless these phenomena are understood, the effect of critical design parameters such as leakage inductances and junction characteristics will remain intangible, and reliable operation of the high-power PPE would always be doubtful in terms of safeguarding against physical as well as performance failures.

Complete modeling and analysis of these phenomena are by no means easy; accurate and practical transient models are presently lacking for both magnetics and semiconductors. The lack of effort was indeed quite inconsistent with our appraisal of the extreme importance of this particular task - one that will likely provide the most fundamental contribution to the current state of power processing technology. It is planned that this extremely difficult task be conferred with due attention in Phase B, aiming for the formulation of methodology on modeling and analysis of the fine details regarding these transient phenomena.

A successful implementation of the aforementioned two approaches allows the entire arsenal of the current statistical reliability analysis to be used, this time with a new level of confidence to ascertain the reliable operation of the PPE and PPS.

7.5.5 PPE/PPS Modeling and Analysis - Performance Evaluation

Performance evaluation concerns the analysis and prediction with regard to how power and control circuits are working in unison to achieve a given set of input/output requirement specifications. Discussed previously in Section 7.3.4, two major areas of interest are: (1) the PPE static and dynamic output response (regulation, audio-susceptibility, conducted interference, output ripple, output impedance, step line and load transient responses including fault) and (2) stability.

To conduct the performance evaluation, analytical methods used can be classified as the following:

- (A) Close-form mathematical analysis using either a frequency-domain equivalent-circuit model^[12,30] or a time-domain model.^[25]
- (B) Computer simulation of actual duty-cycle switching.^[22]
- (C) Computer calculation based on mathematical formulation of time-domain equations

For category (A), various methods available for this program and their relative merits and drawbacks were discussed in Appendix 11.9, and are summarized in Table 13.

Performance evaluation based on frequency-domain linearized equivalent-circuit has been reported.^[12,30] The treatment, so far, has been largely limited to small-signal stability and small-signal ac performance. One analysis, using the Z-Transform method, was able to deduct certain transient-performance criterion for a constant-frequency converter.^[21] The use of a continuous equivalent model, however, prevents the extension of that analysis into discontinued modes of PPE operation, i.e., the operation during which the current in the main output filter vanishes for a portion of the power-switch off time. While it is desirable to possess

closed-form solutions to all performance characteristics, the enormous complexities in handling a complete PPE or PPS (with all the filtering, control and protection functions) generally render this approach impractical except for certain simplest problems with precisely-defined operating constraints. [16, 17]

For category (B), digital computer programs such as TESS and CSM/O/P described in Appendix 11.10, are used to simulate each PPC and/or PPF within the PPE. Complexity is of a lesser problem so long as the computer capability is not exceeded. However, unless a dedicated computer is made available, the computer time can be prohibitively long from the cost viewpoint, especially when iterations of computer runs are needed to deduct any qualitative generality. During Phase A, a series-switching buck regulator with a multiple-loop control circuit was simulated using the TESS program. Appendix 11.21 presents the circuit model input data and the plots of output data exhibiting the duty-cycle switching of the regulator. For calculating five complete switching cycles of operation, the computer operating time for the run was more than seven minutes. Consequently, although good correlation was obtained between the computer model and the breadboard model, the practical utility of this approach, for general use, is likely limited by its cost. Consideration of practical utility also precludes the use of analog computers. Since the ultimate objective of all modeling and analysis computer programs is for the convenient use by all PPE and PPS designers, the awkwardness of technology transmittal associated with the analog computer, along with its dynamic range or frequency spread problems, disqualifies it as a convenient simulation vehicle.

The greatest promise of obtaining a practical engineering tool for PPE/PPS modeling and analysis thus rests on the successful implementation of method category (C). In view of these limitations and the advantages of a discrete time model over a continuous model in terms of duty-cycle limit cycle stability (See Section 7.3.4), the best analytical tool that can be developed during Phase II is expected to involve a time-domain discrete model, for which the time-domain equations will be derived. Based on these equations, a FORTRAN computer program will calculate the various performances in a cost-effective manner.

7.5.6 PPE/PPS Modeling and Analysis - Cost

The practice of certain common senses for future cost savings includes the use of proven design concepts, the reduction of parts count, and the early establishment of firm requirements to minimize the PPE specification changes. Other than these common assertions, which may not always be applicable for various technical reasons, not much concrete methodology can be declared about cost optimization.

For those dealing with the PPE/PPS design, development, and production, it is abundantly clear that there exists very definite tradeoff possibilities among cost, weight (and efficiency), reliability, and performances. Somewhere someone knowledgeable, preferably the PPS designer, would have to weigh the various compromises between what can be done in terms of weight, reliability, and performance, and what is advantageous from the PPS cost perspective to actually acquire. These compromises, once defined, must be adequately reflected in the specified PPE/PPS requirements to effect cost savings. The PPE/PPS modeling and analysis program, while technical in both its temperament and its content, should never lose sight of the role it is capable of making in cost reduction by intelligently defining the PPC/PPE/PPS requirement specifications. This is becoming particularly imperative in view of other emerging, fund-competing programs such as mass transportation, pollution control, and other high-priority civil systems.

A successful modeling and analysis program on weight, reliability and performance is, by itself, the most direct contribution toward PPE/PPS cost reduction. Once the needs are diminished for: (1) time-consuming preliminary tradeoff study, (2) wasteful iterations in design and development to meet requirement specifications, and (3) frequent maintenance due to inadequate design, a methodology for cost optimization would be much easier to formulate. It is for this reason that the modeling and analysis of PPE/PPS cost is scheduled as the last milestone for the Phase B program.

7.5.7 Added Complexity of PPS Modeling and Optimization In Addition to Those of PPE

The fundamental purpose of the power processing system (PPS) aboard a spacecraft is to provide the electrical compatibility between energy sources and various loads. To fulfill this role within the spacecraft optimum criterion, the PPS configuration would have to consist of an optimum combination of PPE. While the identification of interdependencies among various PPE functional blocks is a key procedure in optimizing a PPE, likewise the interdependencies

among various PPE comprising the PPS is instrumental to realizing an optimum PPS. The interdependencies among PPE are likely oriented toward the different requirements imposed on the PPE as a result of different PPE combinations, for these requirements invariably find their way to effect the detail design of each individual PPE functional block.

Therefore, for a given PPS configuration, the different involvements between PPS and PPE modeling and optimization include at least the following: (1) the added complexity of a PPS comprising a multiple PPE; and (2) the identification of each PPE's requirements as a function of the PPS configuration. However, the basic modeling and optimization techniques developed for the PPE are also applicable to the PPS.

8. PHASE B PROGRAM PLAN

8.1 INTRODUCTION

The program Phase I effort is brought to a productive conclusion - the preparation of the Phase B Program Plan. In laying out an integrated, coherent program to bring all aspects of the proposed methodology to a useful form, it is important to define first the specific program goals. These goals have been reflected throughout the previous sections of this report and are summarized in Section 8.2.

Due to the complex nature of the program, certain basic philosophy must be adopted to guide the long-range Phase B program. The discussion is given in Section 8.3.

Guided by the philosophy outlined, the basic Phase B program tasks and their schedule plans are presented in Section 8.4.

8.2 PHASE II PROGRAM GOALS

The general objective of the Phase B program is to implement the PPE/PPS modeling and analysis methodology formulated in Phase A, so that the results of Phase B can be useful in developing future PPS's for the shuttle, the sortie laboratory, the earth orbiting spacecraft, the planetary spacecraft (electric propulsion), and the military aircraft.

The program will be useful to future PPS's in the following primary areas:

- (1) Optimum PPS Weight
- (2) Enhanced PPS Reliability
- (3) Predictable and Improved PPS Performance
- (4) Minimum PPS Cost

Specific goals for each area are described next.

Optimum PPS Weight

At the conclusion of the Phase B program, accurate PPE/PPS analytical models will have been computer programmed to eliminate laborious iterations during PPE/PPS weight optimization tradeoff studies. The program will also include the following features:

- Automated optimum magnetics design.
- The establishment of a power processing component data bank (including power source characteristics).
- The capability of determining the impact on PPE/PPS weight exerted by different duty-cycle control methods.
- Accurate assessment of the weight impact of PPE mechanical packaging.
- The elimination of any overspecified PPE requirements to minimize the weight penalty.

Enhanced PPS Reliability

The program goal here is not to improve on the present statistical approach to the reliability evaluation, but rather to enhance the validity on which the statistical analysis is based. Specifically, the following accomplishments are anticipated from Phase B

- Macroscopically, the reliability will be enhanced by the recommendation of standardized peak-current limiter and active switching transient energy recovery networks to control the peak energy dissipation during any transient operation.
- Microscopically, magnetic-semiconductor hybrid circuit recurrent or incidental switching transient phenomena will be better understood with regard to the effect of stray parameters (leakage inductance, junction characteristics, etc.) on the peak energy dissipation and switching voltage spike associated with the semiconductors.

Predictable and Improved PPS Performance

The Phase B program, concerning PPS performance, is expected to maintain a proper balance between qualitative understanding and quantitative analysis. The specific goals are the following:

- The evaluation of all available analytical tools from which the one most suitable for switching-regulator analysis will be identified.
- The most capable control-circuit concept (single-loop, multiple loop, the method of sensing the types of duty-cycle control, and the method of analog signal to discrete time interval conversion) will be identified in terms of their respective ability to achieve high performance in stability, line/load step transient response, audio-susceptibility, and output impedance.
- The design criteria for performance characteristics other than those intimately related to the control circuit, such as the output ripple, the oscillator starting, etc., will be established.
- The computer program used for performance calculation will be cost-effective in terms of the data-processing time needed.
- Although subject to further study, our present appraisal identifies the time-domain discrete model as the most accurate and general in switching-regulator analysis.

Minimum PPS Cost

- The Phase B program on weight, reliability, and performance will provide the PPS designer with more insight and better judgment on the decision-making with regard to the definite tradeoff possibilities among cost, weight, reliability, and performance.

- Furthermore, cost-reduction is possible at the conclusion of Phase B due to the elimination of:
 - (1) time-consuming iterative tradeoff studies,
 - (2) wasteful design, development and analytical effort.

8.3 PHASE B PROGRAM PHILOSOPHY

Like any systematic study, certain basic philosophy must be adopted to guide the sequential activities. These guidelines are established as the following:

(1) Long Range Program

The enormous contents within the scope of PPE/PPS modeling and analysis, the conjunction with the original nature of most of the tasks to be proposed, would dictate a long-range multi-year program for Phase B. Current appraisal suggests a six-year program for Phase B.

(2) Tasks of Progressive Complexity

The long-range program should be based on a solid foundation. To minimize the Phase B program cost, the technical effort must be planned so that tasks of higher complexity can utilize the modeling and analysis techniques developed during prior, simpler tasks. Practice of this philosophy includes the following analytical sequences:

- From single-loop control system to multiple-loop control.
- From buck switching regulator to other more complicated types.
- From dc system to ac system.

(3) PPE Fundamental to PPS

While the PPS modeling and analysis is the ultimate objective, it cannot be performed without a thorough modeling and analysis on the various types of PPE constituting the PPS configurations. The fundamental importance of PPE study should be reflected in the cost and schedule of the Phase B program.

(4) Explicitness to Intangibility

Modeling and analysis tasks that are capable of being fully formulated by clear expressions will be undertaken first. Consequently, of the four primary areas of program concern listed in Section 8.2, the order of analytical progress will be weight and performance, reliability, and cost.

8.4 PHASE B PROGRAM PLAN

Complete Phase B modeling and analysis efforts are illustrated in Figure 4. The six-year program contains two basic categories:

- (1) Power processing equipment
- (2) Power processing system

Since various PPE serve as building blocks for all PPS configurations, a successful PPE modeling and analysis is fundamental to accomplishing the ultimate program objective concerning the PPS's. Consequently, the PPE modeling and analysis will account for a major portion of the Phase B program effort, and will be conducted prior to the initiation of most PPS activities.

Weight, performance, reliability, and cost are the common primary concerns for both PPE and PPS. In the following subsections, the structural framework of each of the four aforementioned concerns will be presented. Supplemented by the previous discussions given in Section 7, the objective and the overall implementation involvement for all subtask blocks shown in Figure 4, should become evident.

8.4.1 Power Processing Equipment Reliability

Statistical approaches currently used for PPE failure rate analysis will be retained. Major improvements, however, will be concentrated on the positive control of electrical stresses on all power processing components under transient operations to enhance the validity of the statistical approach. Only through this assurance can the PPE reliability approaches as exhibited by the aggregation of the PPC's within the PPE.

Incidental transient stress control will be studied through the philosophy and the functional compatibility of various active means of peak current limiting in the power switch. Recurrent

switching transient stress control will be gained by first securing a better understanding of the magnetic-semiconductor hybrid switching circuits. High frequency magnetics and semiconductor models are necessary, from which various tasks listed in the second column of Figure 4 will be consummated at the end of the fourth year of Phase B.

Computer simulation (i.e., programs such as TESS) will be extensively used as a modeling and analysis tool. The end result is the generation of a set of guidelines prescribing the design of high-power magnetic-semiconductor converters and inverters, with emphasis on the peak-energy dissipation and switch-voltage spikes associated with these equipment. When necessary, the design guidelines will include the modeling and analysis of certain passive and active energy suppression networks.

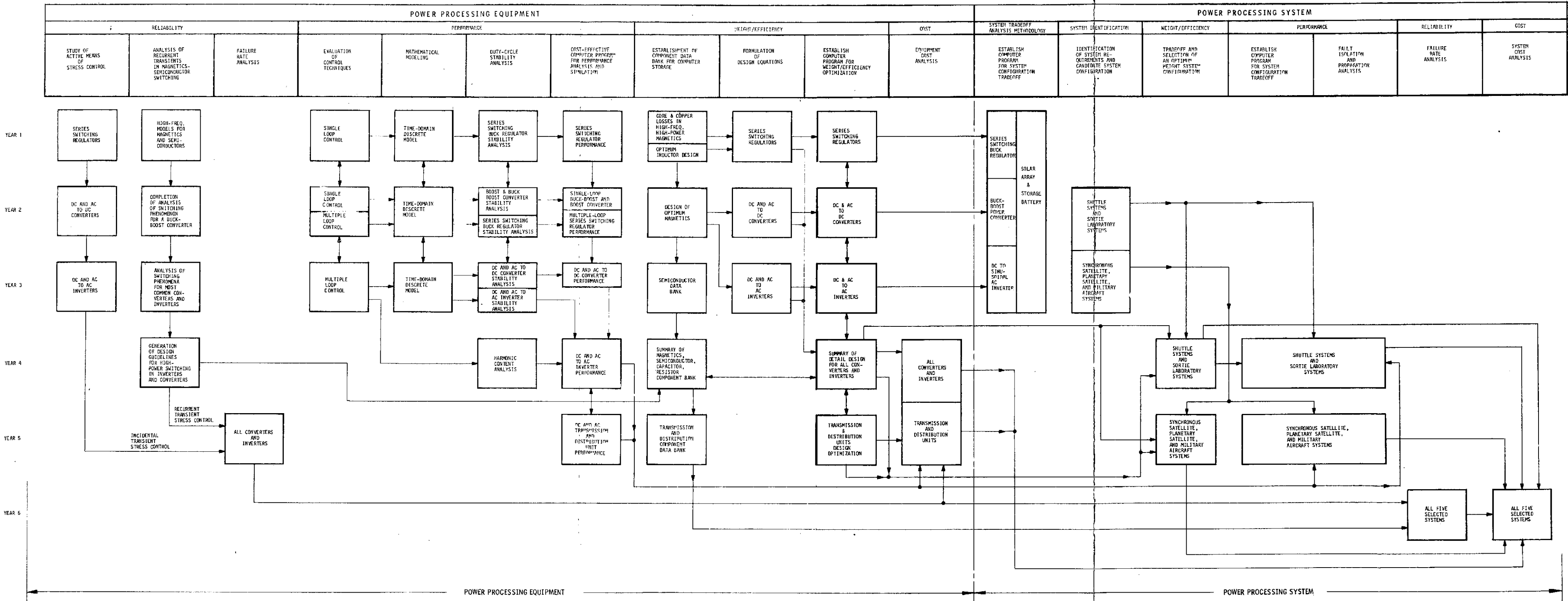
8.4.2 Power Processing Equipment Performance

With the PPE performance characteristics intimately related to the PPE control circuit, performance analysis naturally will start with the control circuit and its analysis, which includes both single and multiple-loop control. Time-domain discrete models are expected to be the leading method of attack, based on which the limit-cycle stability for all regulated PPE will be analytically determined.

Other performance characteristics, such as audio-susceptibility, output impedance and step transient responses, will be calculated by a computer program based on discrete time-domain equations. By virtue of the fact that the computer is asked, in this case, only to perform numerical calculation rather than to simulate the actual act of duty-cycle switching operation, the cost for executing such a computer program will be significantly lower than simulation, thus making it a practical tool for future PPE designers.

PHASE B MODELING AND ANALYSIS PROGRAM PLAN

FIGURE 4 Phase B Modeling and Analysis Program Plan



FOLDOUT FRAME

FOLDOUT FRAME

FOLDOUT FRAME

Other characteristics of importance include output ripple, harmonic contents (in dc to sinusoidal ac inverters) and output regulation. The output ripple will be a design constraint for the weight analysis to be discussed later. Analysis of harmonic content will be part of the year-4 effort, and is expected to reveal the superiority of the constant carrier frequency pulse-width modulation as the premium harmonic-reduction technique.^[22] Analysis of output regulation is in a class by itself, as none of the ac performance analysis technique is applicable here.

8.4.3 Power Processing Equipment Weight/Efficiency

Due to the potentially high degree of explicitness one can obtain in formulating the PPE weight/efficiency, this task is particularly suitable for a computer design optimization. Necessary ingredients for such a program include a set of well-conceived guidelines in optimum magnetics design, an electronic component data bank, and the formulation of power circuit design equations based on the PPE input/output requirement specifications. These design equations should also reflect the PPE packaging impact, for which an accurate model is needed.

All these ingredients, appearing in equation constraints, are to be integrated into a computer program, which solves their simultaneous solutions. Such a program, the Sequential Unconstrained Minimization Technique (SUMT), has been identified during Phase A. The solutions not only represent a minimum-weight PPE, they also provide the detailed PPE design down to the component level.

In view of the present inadequacy in conducting PPE weight tradeoff studies for a given set of input/output requirements, the utility of the modeling and analysis results obtained from this program cannot be underestimated.

8.4.4 Power Processing Equipment Cost

Present cost analysis focuses heavily on a set of empirical rules based on dollars per part. The basic rule is not expected to change for the cost analysis during year-5 of Phase B, primarily because the cost of PPE mechanical packaging will remain parts-count sensitive. However, successful completion in PPE reliability, performance, and weight analysis will significantly reduce the risk of overrun in terms of the future PPE design, development, and analysis cost. Thus, although in all likelihood, the parts count will still be the basis used to perform future cost analyses, the cost prediction, based on the Phase B program results, should be more reliable than its present counterpart.

8.4.5 Power Processing System Weight, Performance, Reliability, and Cost

Basic modeling, analysis, and optimization techniques developed for PPE are also applicable to the PPS. However, a PPS can be comprised of many different combinations of PPE, with each combination forming a unique PPS configuration. Furthermore, different input/output requirements exist for each component PPE within the respective PPS configurations.

For the PPE modeling and analysis techniques to be useful to PPS, one must first identify all candidate PPS configurations and the corresponding requirements for each PPE within a given PPS configuration. This need is reflected in Figure 8.1, prior to the PPS weight, performance, reliability, and cost (WPRC) analysis. Once this need is fulfilled, the WPRC analysis for each PPE within each PPS configuration can be carried out, based on techniques already developed for PPE, and the WPRC of a given PPS configuration is simply the mathematical WPRC aggregation of all PPE within that PPS. Repetitive determination of the respective WPRC for all candidate PPS configurations ultimately provide the PPS designer with all the characteristics relevant to his PPS tradeoff study, from which he can select, unflinching and without presumption, the optimum PPS configuration.

9. DETAILED PLAN FOR YEAR 1

9.1 INTRODUCTION

With the 6-year Phase B program being planned for developing techniques to provide a lasting utility in power processing equipment and system (PPE and PPS) modeling and analysis, the specific tasks planned for year-1 of the long-range program will be oriented toward establishing a solid foundation for the overall program. However, the first year plans of the Phase B program have been formulated so as to provide immediate, tangible and beneficial results at the end of the first year.

Since PPE is the basic constituent of a PPS, by necessity, the first-year work will be mostly confined to the PPE level. Furthermore, no aspect involving cost will be pursued during year-1, for a good understanding on the weight, reliability, and performance aspects is essential to a non-superficial cost analysis.

9.2 BASIC TASK CATEGORIES FOR YEAR-1

Basic task categories for year-1 are presented in Figure 9.1, first row. They are discussed briefly as the following.

9.2.1 PPE Reliability

The first year work on PPE reliability is aimed to enhance the validity of the current method of statistical failure rate analysis. As elaborated previously in Section 6, the failure rate analysis is valid only if the electrical stresses on all PPC's within the magnetic-semiconductor PPE are positively controlled. While stress control during steady-state operation is generally well attended to through nominal design effort, stress control during electrical transients has been frequently an ignored art. These transients can be classified into two types: (1) incidental, and (2) recurrent.

Study of Active Means of Stress Control

Incidental transients include conditions such as step line and load changes, with equipment starting and load short-circuit or arcing as special cases. Electrical stresses on most PPC's

are related to the current build-up in the main filter inductor; active means of stress control must be devised to provide the peak inductor current limiting during these transients. Part of the year-1 reliability enhancement effort will be the study of the nature and the control of the instantaneous current level in the inductor, using a series switching buck regulator as an example. In the subsequent years, the study effort will be extended to other PPE types.

Analysis of Recurrent Transients In Magnetic-Semiconductor Switching

Recurrent transients occur in each cycle of the PPE normal switching function. Manifestations of these transients are generally found in the peak-energy dissipation and the switching voltage spike associated with a semiconductor, although they are in reality also subtly causing other phenomena such as undesirable limit-cycle oscillation and, as a special case, failure to sustain oscillation. Analyses of these transients are, admittedly, difficult indeed. However, the critical importance of these transients to a reliable PPE operation, particularly in view of the future high-power requirement, provides a compelling impetus of including these analyses in the modeling and analysis program. The analytical effort will be initiated by the generation of proper high-frequency equivalent circuits for both the magnetics and semiconductors. Computer simulation programs such as TESS will be utilized as a tool to aid the study. A basic two-winding buck-boost power configuration will be used during year-1 to incorporate the equivalent circuits. The reasons are:

- It contains both magnetics and semiconductors.
- The two-winding inductor allows the modeling and analysis of the effects of leakage inductance and winding capacitances.
- The study will provide insight into the more complicated operation of an inverter using a rectangular-loop core when it saturates during each cycle (or each half-cycle if the core is operated in the minor loop) of normal operation.

Actual completion of the buck-boost converter switching transient study is expected at year-2.

9.2.2 PPE Performance

The first-year work on PPE performance is aimed to establish the basic analytical models and tools that will enable the future development of a complete, accurate and cost-effective PPE performance analysis and simulation computer program. While the evaluation of performance characteristics such as stability, audio-susceptibility, output impedance and step transient responses will command the primary attention here, other characteristics such as regulation accuracy and harmonic contents are not to be overlooked. Specific outputs expected from the year-1 PPE performance analysis are discussed in the following categories:

Evaluation of Control Techniques

Although control techniques include the classical single-loop control and the more recent multiple-loop control, the objective of establishing the most applicable analytical tools will be better served if the first year work starts with the single-loop. Since a control approach cannot be evaluated without its complementary power circuit, a series switching buck regulator will be used for this purpose.

Mathematical Modeling

Analytical effort can be based on time-domain discrete model, frequency-domain continuous linearization model, computer analysis/simulation, and any combination of these methods. While these approaches will be further reviewed to determine their respective utility to the analysis and modeling program, our current appraisal prefers the adoption of the time-domain discrete model. At the end of year-1, discrete time-domain model of a single-loop controlled series-switching buck regulator will have been established, and all time-domain equations formulated.

Duty Cycle Stability

Operating duty-cycle stability analysis is fundamental to the analysis of all other control performances. In the frequency-domain model, stability analysis is generally based on Nyquist criterion and/or Bode plot. In the discrete time-domain model, stability of the steady-state solution can be assessed more rigorously by examining the eigen-values associated with a state matrix describing the steady-state equilibrium solution. This method of attack, as applied to a switching buck regulator for initial illustration, will receive ample attention during the first year, the lack of its previous applicaiton in power processing analysis notwithstanding. At the end of year-1, the completion of a duty-cycle stability analysis using the time-domain approach is expected.

Cost-Effective Computer Program for Performance Analysis and Simulation

In view of the complexity to be encountered in analyzing a power processing system (currently scheduled for year-4, see Figure 8.1), it is essential that such PPS performance characteristics as (1) the output response to step or sinusoidal line/load changes and (2) system output fault propagation, can be processed numerically and with extreme cost-effectiveness (i.e., does not require long computation time). Both performance analysis, based on mathematical modeling, and performance simulation, based on actual implementation of the duty-cycle switching mechanism, are possible, and the task of the first year is to identify and develop the numerical approach that is both accurate and cost-effective. The series switching buck regulator used in the stability analysis will also be the illustration vehicle for the computer performance analysis/simulation.

9.2.3 PPE Weight/Efficiency

The first year's work on PPE weight/efficiency is aimed to initiate the necessary mathematical as well as design implementation, which will culminate in an inclusive computer program for weight/efficiency design optimization, thus eliminating the presently-arduous equipment or system tradeoff study and achieving simultaneously accuracy and cost-effectiveness. To gain such a goal encompasses three basic tasks: (1) the assembly of a computer data bank for the power processing component (PPC), the formulation of design equations, and (3) the establishment of a compatible computer technique.

Component Data Bank for Computer Storage

While the data bank eventually would include all electronic components, only the magnetics component will receive the first-year attention. In particular, the core-loss and copper-loss data associated with high power, high frequency magnetics under asymmetrical squarewave excitation are presently lacking; they will be identified through experimental/analytical investigations to facilitate an optimum design for the output filter inductor of the aforementioned series-switching buck regulator. At the present time, it suffices to point out that the lack of published information concerning magnetics losses has been a fragile link blocking a comprehensive optimum magnetics design; such a design is instrumental in achieving an optimum PPE weight or efficiency.

Formulation of Design Equations

As described in Section 6, design equations for all power processing functions within the given PPE must be formulated to facilitate an optimum-weight PPE design. In year 1, these equations will be formulated for the previously-mentioned series switching buck-regulator power circuit. Emphasis will be placed on the derivation, in closed mathematical form, the weight/loss associated with each PPC, and the constraints relating the design parameters to the various PPE specifications. Furthermore, the use of the

specifications and the optimization criteria (either weight or efficiency) as the fibers linking the interdependences among the various PPF's will also be demonstrated.

Establish Computer Program for Weight/Efficiency Optimization

The computer program to be established in year-1 will be capable of solving the simultaneous equations formulated, for the series switching buck regulator, thus providing the detail design of its power circuit down to the component level. Since a detailed data bank is not yet available in year-1, certain numerical values required as computer inputs, such as the capacitor weight for a given capacitance with a predetermined voltage rating, will be assessed on the basis of design experience. This practice is deemed acceptable in view of the fact that the first-year objective is to establish the basic computer technique rather than to accomplish a fully automated design.

9.2.4 Power Processing System Tradeoff Methodology

Having performed all the year-1 tasks listed previously concerning a PPE, work will be initiated to engage a study on the system tradeoff analysis methodology. The major objective here is the investigation on how the basic information gained from the year-1 PPE analysis can be most effectively utilized, in an organized and orderly fashion, to achieve an optimum PPS design. To serve this purpose, a simple fictitious PPS containing a solar array, a storage battery, and a series-switching buck regulator, will be used as an illustration to achieve a minimum system weight. In other words, the sum of the switching regulator weight and the incremental solar-array and storage-battery weight needed to supply losses in the switching regulator, will be minimized.

9.3 STATEMENT OF WORK

9.3.1 Objectives

The objective of the first-year work outlined herein is to provide a solid foundation for the long-range modeling and analysis program. The foundation is pertinent to the achievement of the following ultimate program goals:

- (1) To enhance the validity of the present statistical approach of the failure rate analysis through analytical study of component stress control during incidental and recurrent transient operations.
- (2) To develop the basic analytical model for power processing equipment performance evaluations and to establish a cost-effective computer program for performance analysis and simulation, using a series-switch buck regulator as an example.
- (3) To establish the basic computer technique for:
(a) power processing equipment weight/efficiency optimization, using the series switching buck regulator as an example, and (b) power processing component data bank storage. The component study includes the computer routine for the optimum design of minimum weight inductors.
- (4) To establish, through a practical example, the basic power processing system analysis methodology in preparation of future tradeoff studies of more complicated systems.

9.3.2 Specific Tasks

The contractor shall provide the necessary personnel, materials, and facilities to perform the work described in the following tasks:

TASK 1. Power Processing Equipment Design, Analysis, and Weight (or Efficiency) Optimization

Design equations shall be generated for a series-switching buck regulator with an input rating of 60V and 300W maximum, which shall include input and output filtering, power stage modulation, inversion, rectification, and the effects of the different duty-cycle control on the design of these power processing functions.

The design equations shall be solved by appropriate computer techniques to establish the design parameters of all components as related to the requirements specifications of the buck regulator, the optimization criterion (weight and efficiency) and

the significant interaction with the feedback control system. The solutions shall include the determination of the optimum switching frequency for the buck regulator. The solutions shall also include the detailed design parameters of the power inductor such as the dimension of core, winding turns and wire size, and the permeability.

Initial effort leading to the ultimate establishment of a component data bank shall include an experimental/analytical study of losses in high frequency, high power magnetics under asymmetrical squarewave excitation. The study results shall be used in the weight optimization for the aforementioned series switching buck regulator.

TASK 2. Power Processing Equipment Performance Analysis and Simulation

A single-loop feedback shall be used for initial investigation purposes to control the series-switching buck regulator identified in Task 1. Different duty-cycle control such as constant frequency, constant on-time, constant off-time, constant ripple, constant volt-seconds, etc., shall be reviewed as applicable to the series switching buck regulator.

Mathematical models of the series switching buck regulator using the single-loop control shall be generated. Both frequency-domain and time-domain analytical approaches shall be considered in generating the mathematical model. Since the emphasis of the later approach is toward the switching frequency, it shall receive special attention in the operating duty-cycle stability analysis.

Subsequent to the identification of the analytical models, stability analyses shall be performed with the objective of deriving sufficient qualitative generality. Based on the same models, other performance characteristics such as step transient response, audio-susceptibility, output impedance, static regulation and fault operation, shall be evaluated.

A computer simulation program shall be established to aid the performance evaluation. The program shall be cost-effective to run, and shall not rely on the availability of a dedicated computer.

TASK 3. Power Processing Equipment Reliability Enhancement

The validity of the current failure rate statistical analysis shall be enhanced through: (1) study of the methodology to provide the power processing component stress control during incidental transients such as

regulator starting and sudden output short, and
(2) establishment of high-frequency equivalent circuits for the magnetics and the semiconductors to facilitate a comprehensive analysis of the magnetics-semiconductor hybrid circuit switching phenomena, thus providing the basic understanding for controlling the component stress during re-current switching transients. A basic buck-boost power circuit configuration shall be utilized to fulfill the analytical purpose.

TASK 4. Power Processing System Tradeoff Analysis Methodology

The power processing equipment modeling and analysis approaches and results associated with the first three previous tasks shall be collectively examined and integrated into a methodology; the methodology thus conceived shall be aimed at an orderly and cost-effective plan to utilize the basic power processing equipment study results for the benefit of the power processing system tradeoff analysis. The utility of the methodology shall be demonstrated through the weight optimization of a basic power processing system configuration containing a solar array, a storage battery, and a series-switching buck regulator.

9.2.5 Review and Reporting

The contractor shall prepare a presentation at NASA Lewis after the first half of the program, covering results of Tasks 1 through 3 obtained up to that time period.

The contractor shall prepare a final presentation which describes the results of Tasks 1 through 4. A formal, oral presentation of results shall be made at Lewis Research Center. A review draft of the final report shall be submitted to the project manager no later than ten (10) days following this presentation.

In addition:

- A. Technical, financial and schedular reporting shall be in accordance with the Reports of Work (with 533M) attachment.
- B. The contractor shall report data in the "Planned" cost columns 7b and 7d of the NASA Form 533M. This planned cost data shall be taken from the latest plan as approved in the Work Plan, including approved revisions hereto. Column 8b of NASA Form 533M shall contain estimates of costs and manhours for the second subsequent month. The monthly report submission data shall be no more than ten (10) operating days after the closing data of the contractor's accounting month.
- C. The number of copies to be submitted for each monthly report is as follows:
 - 1. A maximum of 15 copies of the Monthly Technical Progress Narrative.
 - 2. A maximum of 5 copies of the Contractor Financial Management Report (NASA Form 533M).
 - 3. A maximum of five (5) copies of the Financial Management Performance Analysis Report (NASA Form 533P).

The reporting categories to be reported in NASA Form 533M with the contractor's monthly reports are as follows:

- a. Tasks 1 through 4 direct hours and dollars.
- b. Total contract direct hours and dollars.
- c. Total contract overhead.
- d. Total cost.
- e. Fee.
- f. Total contract.

9.4 PROGRAM SCHEDULE

A sample program schedule to perform the tasks of the statement of work is shown in Figure 5.

Tasks 1 and 2 are scheduled to overlap to allow a constant information flow between the two tasks. Thus, the effects of control performance on the power circuit design are timely integrated.

Tasks 3 and 4 are carried forward and amplified on in the subsequent year(s) of the program concerning the analysis of the switching phenomena and the sample PPS analysis.

Progress briefing, final briefing, and final report are indicated as milestones in Task 5.

9.5 RECOMMENDED LEVEL OF EFFORT

Each task contained in the statement of work has been estimated with regard to the required manpower and computer time for the fulfillment of the respective technical goal.

In accordance with the program schedule shown in Figure 5, Table 3, lists the recommended hours for the engineering effort and remote computer terminal operating time.

FIGURE 5 Modeling and Analysis Program Schedule Year 1

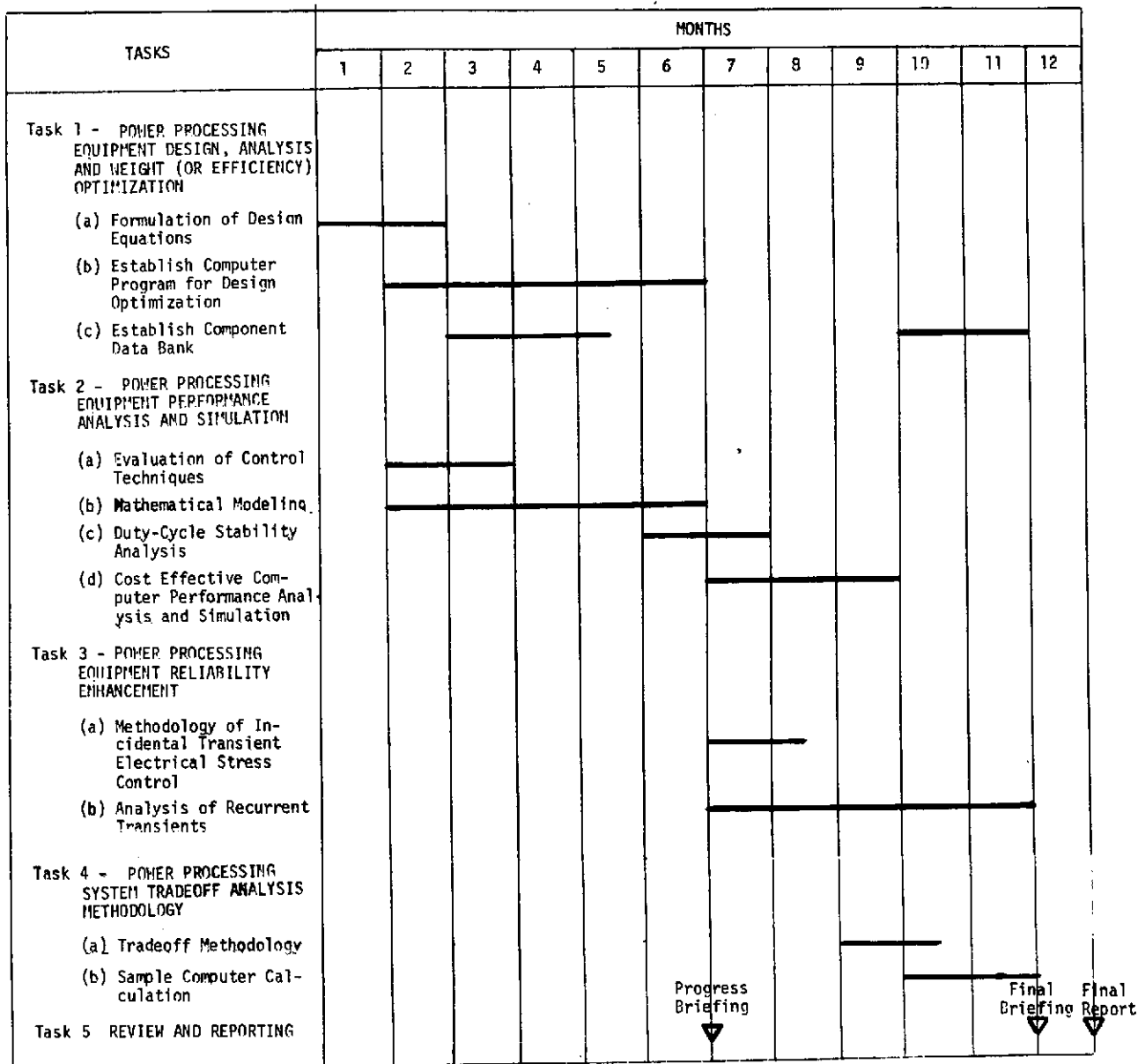


TABLE 3

RECOMMENDED LEVEL OF EFFORT FOR THE YEAR-1 PROGRAM

TASK	ENGINEERING MANHOURS	COMPUTER HOURS (Remote Terminal)
1 - Power Processing Equipment Design Analysis and Weight Optimization	2150	250
2 - Power Processing Equipment Performance Analysis and Simulation	2250	200
3 - Power Processing Equipment Reliability Enhancement	1150	70
4 - Power Processing System Tradeoff Analysis Methodology	500	50

10. CONCLUSION

To anyone working with nondissipatively regulated converters, inverters, and systems comprised of these equipment, certain design and analysis intricacies inevitably make themselves felt throughout the equipment and system design and development stage. Empirical and intuitive reliances often intercede with the designer's desire to be "more scientific" and his commitment of being "on schedule." Handicapped by a general lack of established design, modeling, analysis, and optimization tools, it has not been unusual for a power processing designer to face the perplexing situation of emerging from the intercession practically empty-handed.

Generally speaking, the plight that most equipment and system designers find themselves in has to do with at least one of the following power processing characteristics: weight/efficiency, performance, reliability, and cost. While power processing as a technology has reached the level of sophistication where the modeling, analysis, and optimization of these characteristics should have been well established, a survey of existing documents and literature has proven the contrary.

The primary content of this report focuses the attention on the formulation of a modeling and analysis methodology for power processing components, equipment and systems. Five diversified power processing systems including those of shuttle, sortie laboratory, earth orbit spacecraft, planetary spacecraft, and military aircraft are selected from the space flight programs within the next two decades. These systems will be the specific beneficiaries as a result of the methodology implementation, although the potential beneficiaries will definitely transcend the chosen five.

A six-year program plan was conceived to implement the methodology formulated. Since the system modeling and analysis cannot be

performed without a thorough understanding on the various types of equipment constituting the system configuration, a majority of the initial program effort is centered on the equipment level, with the system aspects phasing in gradually as the equipment modeling and analysis techniques consolidate.

When successfully executed, the six-year program is expected to provide the following flexible design and analysis tools and benefits:

- The power processing equipment and systems which can achieve optimum weight/efficiency through the use of optimization computer programs based on: (1) detailed design equations to satisfy a given specification, and (2) accurate power processing component data stored in a computerized data bank. Such an optimization program would, upon its perfection, relieve the present need for the time-consuming and marginally-accurate system tradeoff studies.
- The power processing equipment and system steady-state and transient performances can be calculated and simulated by cost-effective computer programs. Such programs can be extremely useful, for they allow the assessment of the power processing system performances prior to the system development and integration.
- The current method of power processing system statistical failure rate analysis will not be altered as a result of the six-year program. However, the program outlines a methodology to study and analyze all incidental and recurrent transients within a power processing equipment, with the objective of understanding and controlling the various

transient and switching phenomena so that no power processing component will operate beyond its rating under any condition. Consequently, while the failure rate analysis remains statistical in nature and identical to today's methods, the level of confidence concerning the reliability assessment at the end of the long-range program will be at a higher level than its present counterpart.

- Accurate and successful weight optimization, performance prediction, and reliability assessment, are cost-saving measures themselves. However, another potential outgrowth from these achievements is that they may provide a system designer with certain real and solid bases for the conduction of a cost tradeoff analysis between two diversified philosophies concerning reliability enhancement, namely, whether to implement component and equipment redundancy, or whether to call for modularization. The methodology of engaging this tradeoff is, admittedly, not all clear at this time. However, it should become more apparent as the six-year program advances.

Power processing technology has, by necessity, been rapidly evolving. It is perhaps not an understatement that, in terms of modeling and analysis of the power processing equipment and systems, the level of sophistication has been much below that of equipment/system circuit developments. The industry, however, has reached the maturity that such a gap can no longer be tolerated without incurring severe penalties in the equipment and system weight/efficiency performance, reliability, and cost. It is thus to the advancement of the power processing equipment/system analysis and simulation along with its ultimate fertility to the soil of equipment/system design and development, that this analysis and modeling program is dedicated.

11. APPENDICES

The following is a list of appendices included in support of the main text of this technical report.

- Appendix 11.1 Survey of Future NASA and Military Space Flight Programs.
- 11.2 Important Categories of a Useful Power Processing System Documentation.
- 11.3 List of Power Processing Equipment Classification for the Five Selected Systems.
- 11.4 Source, Equipment and Load Interactions.
- 11.5 Optimum-Weight Magnetics Design to Achieve the Least Combined Weight for the Magnetics and the Power Source.
- 11.6 An Example of Previous Parametric Study Results.
- 11.7 Power Processing Equipment Characteristics Based on Cumulative Power Processing Function Parametric Data.
- 11.8 Existing Control Mode, Control Mechanism, and Modulation Philosophies.
- 11.9 Power Processing Equipment Performance Analysis Methods.
- 11.10 Available Computer Programs for System/Equipment Design, Analysis, and Optimization.
- 11.11 A Detailed Power Processing Equipment Requirement List.
- 11.12 Detailed Definition of Classification of Power Processing Function.
- 11.13 Power Processing Equipment Functional Block Diagrams.

- 11.14 A Numerical Example on the Interdependence Among Power Processing Functions.
- 11.15 An Example of Closed-Form Optimum-Weight Magnetics Design Equations.
- 11.16 An Example of Deriving Design Equations For a Power Processing Function.
- 11.17 An Example of Power Processing Component Stresses as Determined from Functional Design Equations.
- 11.18 General Philosophy of Solving Nonlinear Simultaneous Equations.
- 11.19 An Example of SUMT Application in Optimum Design.
- 11.20 Formulation of Mathematical Equations For a Series Switching Buck Regulator.
- 11.21 An Example of Power Processing Equipment Computer Simulation Using TESS Program.

11.1 SURVEY OF FUTURE NASA AND MILITARY SPACE FLIGHT PROGRAMS

11.1.1 NASA Space Transportation System

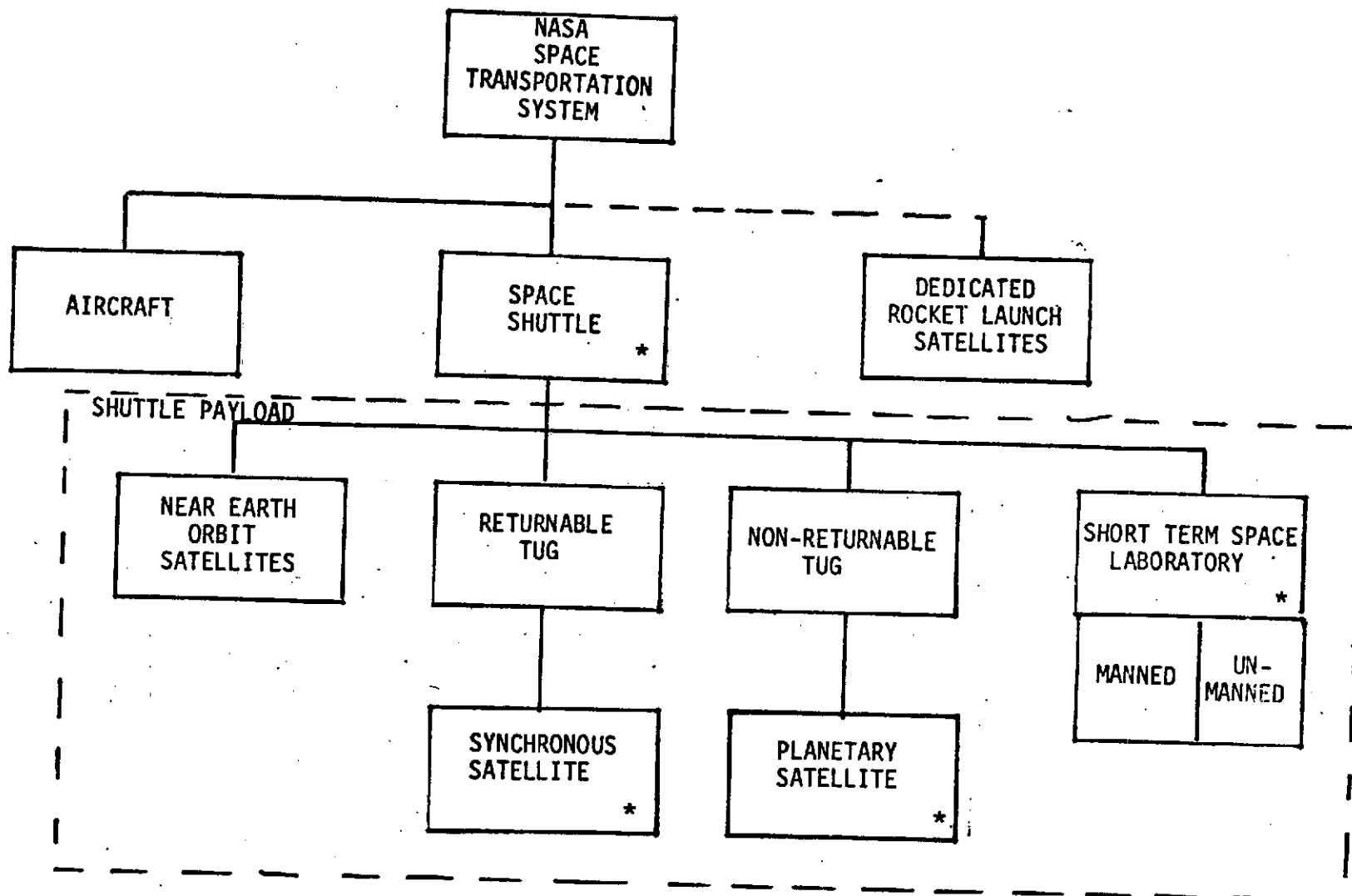
Extensive studies have been performed at NASA to determine their future programs and goals in order to satisfy their technical objectives consistent with the financial allocations.

Figure 6 illustrates the NASA Space Flight programs for the 1975 to 1990 period as related to the NASA Space Transportation System. The primary transportation system for NASA will be the Space Shuttle program, supplemented by aircraft and dedicated rocket launch satellites. The shuttle payload can be NASA programs, military programs, or even European or Japanese programs. These programs can be divided into four basic categories.

The first category includes earth orbit satellites which can be set in orbit and retrieved by the space shuttle itself. These include earth observation satellites, special experiment satellites, communication satellites, or anything in a fifty to one hundred and fifty mile orbit above the earth.

The second category is the returnable tug and its satellite payload. Because of the higher energy to transfer to the synchronous orbit, space shuttle cannot be used for that application. The unmanned tug will be launched from the payload area with its satellite load and will place the satellite in the synchronous orbit. The tug can either place the satellite in orbit or return it to the shuttle for transfer back to earth. This allows a combination of the shuttle, the tug, and a recoverable satellite.

The third category is the non-returnable tug, generally being planned for the interplanetary satellite which must escape the gravitational field of the earth. The non-returnable tug can also be used for placing extremely large synchronous satellites in orbit where the tug does not have the propulsion capability to return to the near-earth orbit for return to earth.



Notes* Selected Power Processing System for Study

NASA SPACE FLIGHT PROGRAM (1975 - 1990)

Figure 6

The fourth category is the short-term space experiments that can last a period of seven to fourteen days. These experiments can be either manned or unmanned. These are located in the shuttle payload area and can be easily removed to change the type of experiments required for the mission.

11.1.2 Military Space Transportation Program

The Military Space Transportation System was also reviewed for this program. Figure 7 illustrates the Military Space Program for the period 1975 to the year 2000.

This figure includes the military aircraft, space shuttle system which is the same system used for NASA, rocket launch satellite, ballistic missile, and military weapon systems.

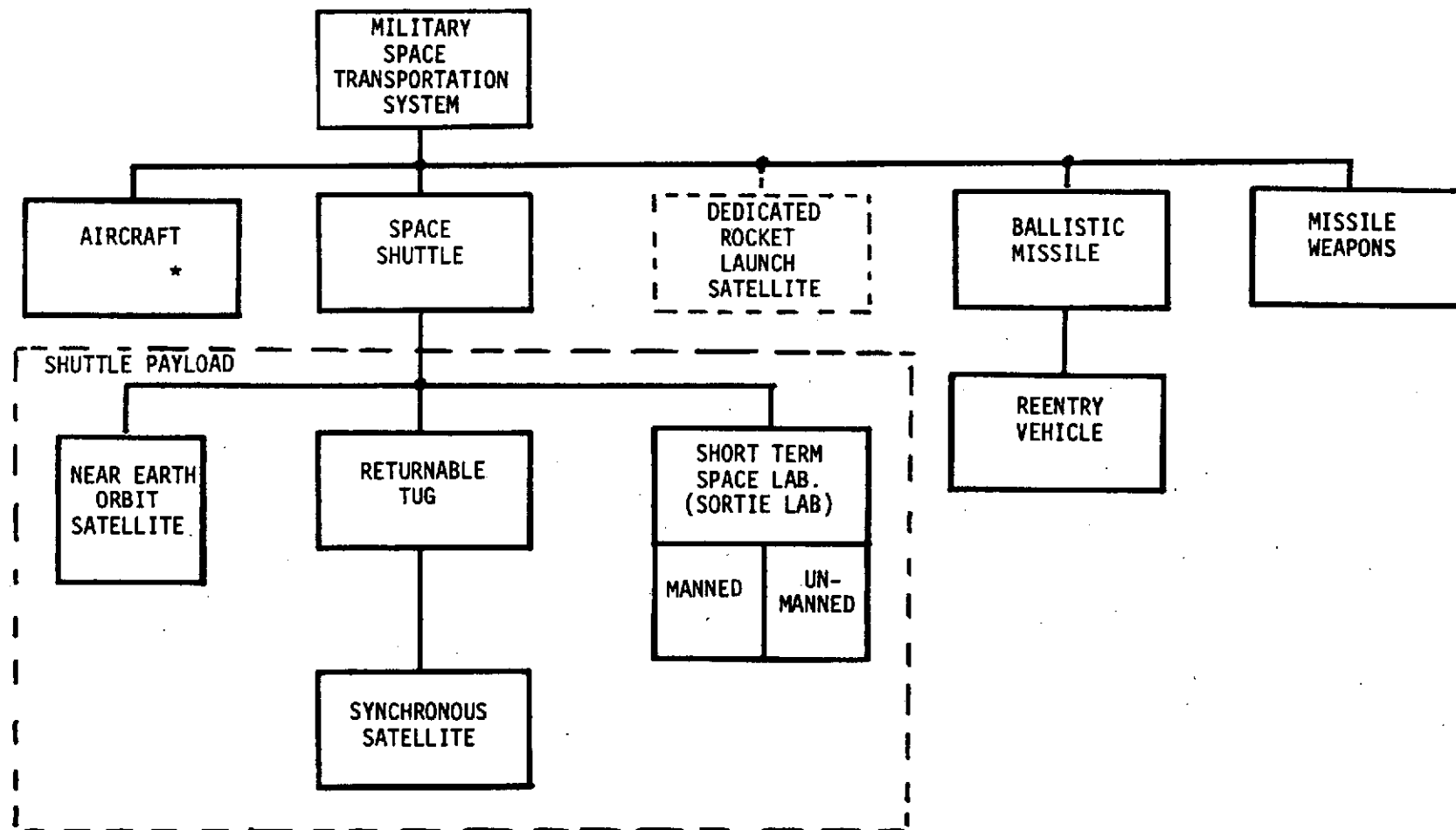
Payloads in the shuttle include the military near-earth orbit satellites and the military synchronous satellites using the returnable tug. Sortie Labs are also being planned for the payload area in the NASA Space Shuttle program.

Dedicated rocket launch satellites are still being planned for special experiments.

Intercontinental Ballistic Missiles and their reentry vehicles are also part of the Military Space Transportation System. In these programs, silver-zinc batteries are used as the power source for the power processing system.

The last category is the Missile Weapon System, either for air-to-air combat or air-to-ground combat. In these systems the power source is the thermal battery which provides power for a very short time period. The Missile Weapon Systems have a dual design constraint of minimum cost and minimum weight.

Notice in Figure 7 that the primary military space transportation system uses the NASA Space Shuttle program as the principal launch vehicle and all aerospace payload programs will be designed to fit into the shuttle payload area.



Notes* Selected Power Processing System for Study

MILITARY SPACE FLIGHT PROGRAM (1975-2000)

Figure 7

11.1.3 Selection of Five Power Processing Systems

In Figures 6 and 7, the PPS's that were selected for the Modeling and Analysis program have been identified. These systems include: (1) the space shuttle, (2) the synchronous satellites which include the near-earth orbit satellites in that they are very similar in design, (3) the planetary satellites which use a different power source and require extremely high reliability, (4) the sortie laboratory using new high-power equipment that have never been used in space before, and (5) military aircraft. The new military aircraft was selected to insure that all possible loads have been identified for the power processing system.

Table 4 summarizes the selected five power processing systems. The table includes mission, power source, distribution voltage, power level, and design constraints for the spacecraft or aircraft.

The space shuttle uses two different types of power source: (1) fuel cell for the electronic and environmental control systems, and (2) an APU (Auxiliary Power Unit) which drives the hydraulic system during launch and reentry. Fuel cells provide 28Vdc and will have a power level of approximately 7kW (15kW peak) for each of three redundant fuel cells.

The returnable tug will include much of the equipment developed for the space shuttle and will also use fuel cells (1.5kW) as the power source. Therefore, the model developed for the space shuttle system can be extrapolated for the returnable and non-returnable tug power processing systems.

The synchronous satellite will use the solar array as the primary power source during sunlight and the rechargeable battery during launch and eclipse operations and for transient peaks. Distribution voltages may include 60Vdc for the high power payload equipment and 28Vdc for the remainder of the satellite equipment. Power levels for the high voltage bus may go as high as 10kW while the 28V bus power will be in the range of 500W.

TABLE 4

SELECTED FIVE POWER PROCESSING SYSTEMS

Mission	Power Source	Distribution Voltage	Power	Design Constraint
Shuttle	Fuel Cell	28Vdc 115/200V RMS 3Ø 400Hertz	3x7 KW	Crew Safety & Reliability
Sortie Lab	Fuel Cell	28Vdc/115V 1Ø 400Hertz 115-208V 3Ø 1800Hertz	7KW to 30KW	Cost, Minimum Design & Fabrication Time
Synchronous Satellite	Solar Array/Battery	100Vdc/28Vdc	10KW/500W	Cost & Maintainability
Planetary Electric Propulsion Satellite	Solar Array/RTG	300Vdc/28Vdc/50V AC 2.4KHz	25KW/500W	Cost & Reliability
Military Aircraft	Primary Engine Generator, Emergency Generator and Battery	230-400V, 3Ø 400Hertz 115-200V, 3Ø 400Hertz 28Vdc	140KW	Cost & Maintainability

The planetary satellites will include mercury ion engines for electric propulsion to reduce the spacecraft flight time and thereby reduce the reliability requirements for the total equipment. The planetary satellite will include a high voltage solar array of approximately 25kW power level to run the electric propulsion engines and a radioactive thermoelectric generator (RTG) at approximately 28Vdc to provide power for the experiments and other electronic loads on the spacecraft. The models generated for the planetary satellite will fulfill both applications.

The sortie laboratory requires both a low cost and extremely short development schedule. The primary power source for the laboratory is a fuel cell in the space shuttle. When the experiment power demands exceed the shuttle capability, additional fuel cells will be added to the sortie laboratory to satisfy total power demands. Expected power levels will range from 8kW to approximately 30kW. These extra fuel cell modules will be added to the payload area in the sortie lab.

Although the military aircraft power processing system has a vastly different load configuration from a commercial aircraft, the model generated can be changed to satisfy the requirements for the commercial aircraft power processing systems. The reason for including aircraft systems is that the power distribution is ac compared to dc for other selected power processing systems.

In review, an attempt was made to select systems that included all the different power sources; fuel cells, solar array, batteries, radioactive thermoelectric generators, and engine generators.

11.2 IMPORTANT CATEGORIES OF A USEFUL POWER PROCESSING SYSTEM DOCUMENTATION

Figure 1 on Page 11 of this report shows the items that affect an optimum power processing system design.

The first item is the specific program design constraints:

- Cost
- Weight
- Reliability

In most future programs, cost is a main design element. The cost not only includes the initial cost (design and fabrication of the equipment), but the cost of maintenance, and the operating cost. In some instances, weight can be a design constraint in that there is a limitation of how much weight can be allowed to have an effective program. In certain future programs, it may be possible that the power processing equipment can be repaired in orbit or upon its return to earth; thus, reliability is no longer an overriding program design constraint. However, the equipment should be designed in such a manner that the equipment failure does not propagate to the power source or to the load equipment. The planetary spacecraft, on the other hand, must be designed with reliability as a primary design constraint. In this application, repair of the power processing equipment is not possible since there is no means of retrieving the satellite.

The second item is the Spacecraft/Aircraft design. This category includes: (1) the size of the craft in that it determines the cable runs from the power source to all load equipment, (2) the payload, whether it is an experiment, a communication system or aircraft electronics, (3) the environment that the unit will be subjected to, (4) the operating time of the unit before it can be maintained and its effect on the design techniques for the reliability of the equipment, and (5) the life requirements that must be designed into the power processing system.

The third item that affects the power processing system is the power source characteristics. This includes the power source type (solar, chemical or nuclear) and the power source density.

The fourth item is the load equipment and its power requirements. The power processing system must process the power to the load equipment so that the load equipment can operate reliably within specification.

The fifth item is the power processing equipment requirements. It must provide the correct interface between power source, the load equipment, and aircraft/spacecraft.

11.3 POWER PROCESSING AND LOAD EQUIPMENT LIST - BLOCK DIAGRAM FOR THE FIVE SELECTED SYSTEMS

11.3.1 Power Processing and Load Equipment Classifications

In order to formulate a concise modeling and analysis program, there must be an attempt to classify the power processing and load equipment, thereby reducing the size of the program.

Table 5 lists the power processing equipment lists for both the ac power distribution system and dc power distribution system.

Five basic categories are included under both ac and dc power distribution systems. The line regulator provides the voltage regulation against variations due to the input power source characteristics and the output loads, with no input-output ground isolation. The ac to dc converter provides the input-output isolation and regulation requirements for the dc load equipment. The ac (and dc) to ac inverter provides both output voltage regulation and frequency control to satisfy the load requirements. Source power control includes breakers, fuses and the feeder cabling between power source and load control units. The load power control system includes localized breakers, fuses and the cabling to the different subsystems.

Table 6 shows the classification of load equipment that includes avionic, propulsion, environmental control, power control and distribution, and payload.

Avionic classification includes guidance and navigation, flight control, data management, data storage, communications and display.

Propulsion system includes the main engine control, auxiliary engine control, the air-breathing engine control, and the mercury ion engine for planetary flight.

Environmental control includes that for manned flight in space, the thermal control of aircraft through its environment, and the control of spacecraft in its environment and fire protection.

TABLE 5

POWER PROCESSING EQUIPMENT LIST

I. AC POWER DISTRIBUTION

- a) AC Line Regulator
- b) AC to DC Converter
- c) AC to AC Inverter
- d) Source Power Control
- e) Load Power Control

II. DC POWER DISTRIBUTION

- a) DC Line Regulator
- b) DC to DC Converter
- c) DC to AC Inverter
- d) Source Power Control
- e) Load Power Control

TABLE 6

CLASSIFICATION OF LOAD EQUIPMENT

- I. Avionic
- II. Propulsion
- III. Environmental Control
- IV. Power Control & Distribution
- V. Payload

Power control and distribution include the control of the power source, the source distribution which may include battery charger, max-power point tracking, and the load distribution.

The payload includes experiments, high power communications, and weapon systems.

In this grouping of power processing equipment and load types, simplification of the modeling and analysis techniques can be obtained.

11.3.2 Space Shuttle System Block Diagram

The space shuttle system is the primary NASA transportation system to be used after 1975 for all space experimentation. It is a manned system and it requires maximum reliability to insure safety of the crew. The space shuttle system is being designed with at least a 10-year operational life in order to be cost effective.

Figure 8 illustrates the basic power processing distribution systems that will be used for the space shuttle. The primary power is from three separate 28Vdc, 7kW fuel cells.

Each fuel cell system feeds a complete shuttle system with all its loads. In this way, there are three identical power processing systems so that two failures in the system will not cause a loss of the shuttle and it can still operate with the third remaining channel.

The main breaker protects the fuel cell. Breakers are used on each feeder line going to different equipment areas of the shuttle. These areas include forward equipment bay, the pressurized equipment bay, left-wing equipment bay, right-wing equipment bay, and aft equipment bay. Each equipment bay has its own dedicated load distribution center which includes additional circuit breakers and fuses to protect against faults in the load distribution cable and load equipment.

One feeder line provides power through a current limit source to the emergency battery. This emergency battery is used during firing of ordinances requiring high peak currents and to supply critical loads during abnormal modes of operation.

Separate battery chargers can take energy from any one of the three fuel cells and charge the emergency battery used in any of the three redundant power processing systems.

In this manner, a very reliable system is realized which is capable of sustaining multiple failures and still be operational, thus providing uppermost safety for the astronauts.

The space tug power processing system is very similar to the shuttle power processing system, but it only includes two redundant fuel cell power processing distribution systems.

SPACE SHUTTLE POWER PROCESSING SYSTEM BLOCK DIAGRAM

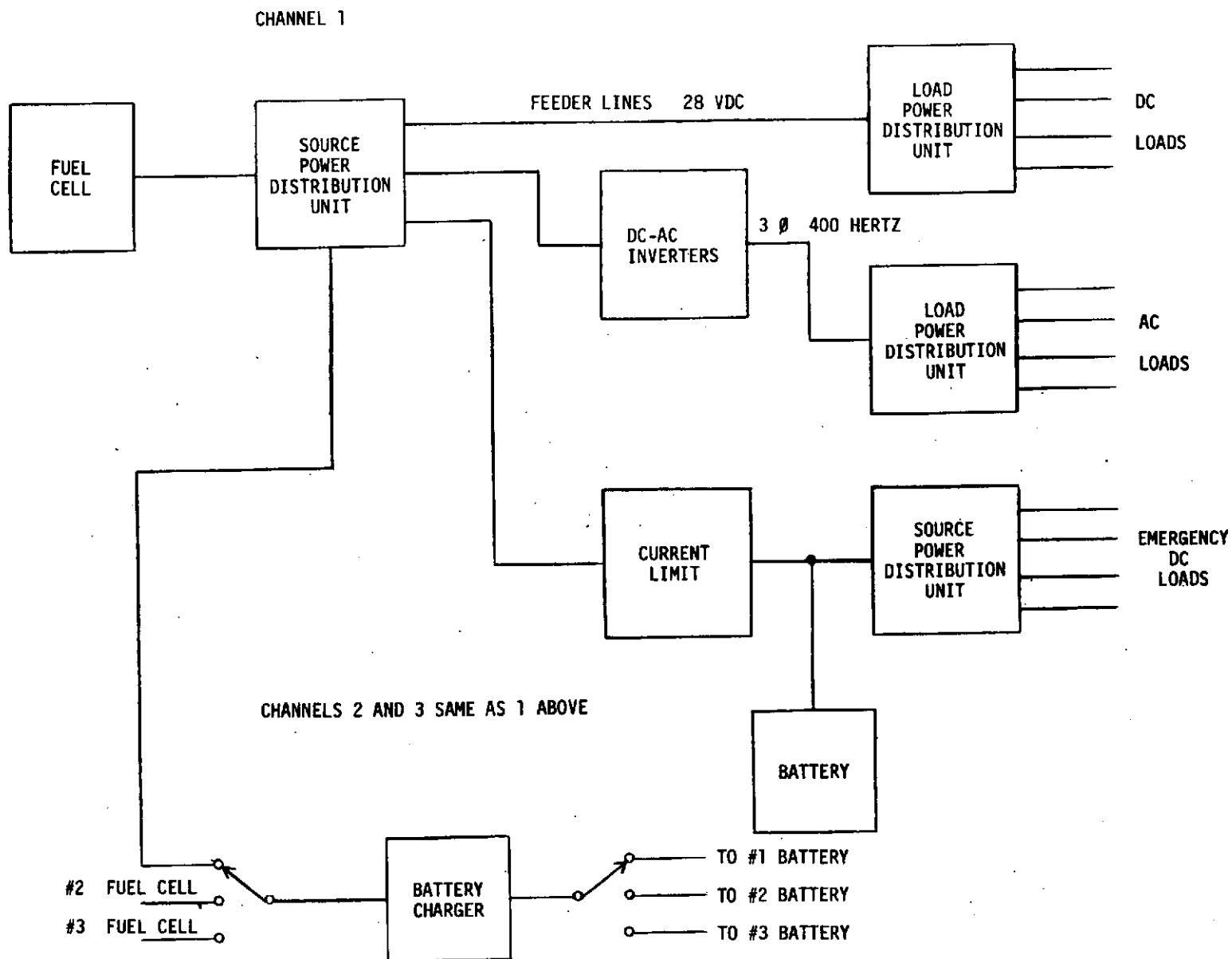


FIGURE 8

11.3.3 Sortie Lab System Block Diagram

Many scientific experiments are being planned for the shuttle program wherein the experiments are mounted in the shuttle payload area. These experiments will last from 7 to 14 days, depending on the capability of the space shuttle itself. These space lab experiments can be either manned or unmanned, depending on the type of scientific data being obtained. The primary objective of the space laboratory is to allow extremely low cost, fast redesign and turn-around of equipment and use of existing hardware whenever possible.

Figure 9 illustrates the power processing system for the space lab. Twenty-eight volts from the shuttle fuel cell are inverted to 115V, 400 Hertz, to operate all the low-power equipment. Total power capability of the system is approximately 7kW. For extremely high power experiments, additional fuel cell modules will be added to the shuttle payload area to provide power to the experiments. This 28Vdc power will be inverted to high-voltage, 3-phase high frequency power to supply the special experiment loads.

An additional 400 Hertz inverter will also be included to supply other additional low power test equipment. It is expected that the space lab module will be adapted to scientific experiments and will have many more applications. It is important that we establish optimum low cost designs for this power processing system.

11.3.4 Synchronous Satellite System Block Diagram

Synchronous communication satellites have the highest power requirement and are being used as basic models for all earth orbital satellites. This model can be interpolated to form a power processing system model for all other systems. The principle difference between the synchronous satellite and near-earth orbit satellite is the ratio of eclipse to sunlight time and the amount of energy storage in the battery system.

SORTIE LAB POWER PROCESSING SYSTEM
BLOCK DIAGRAM

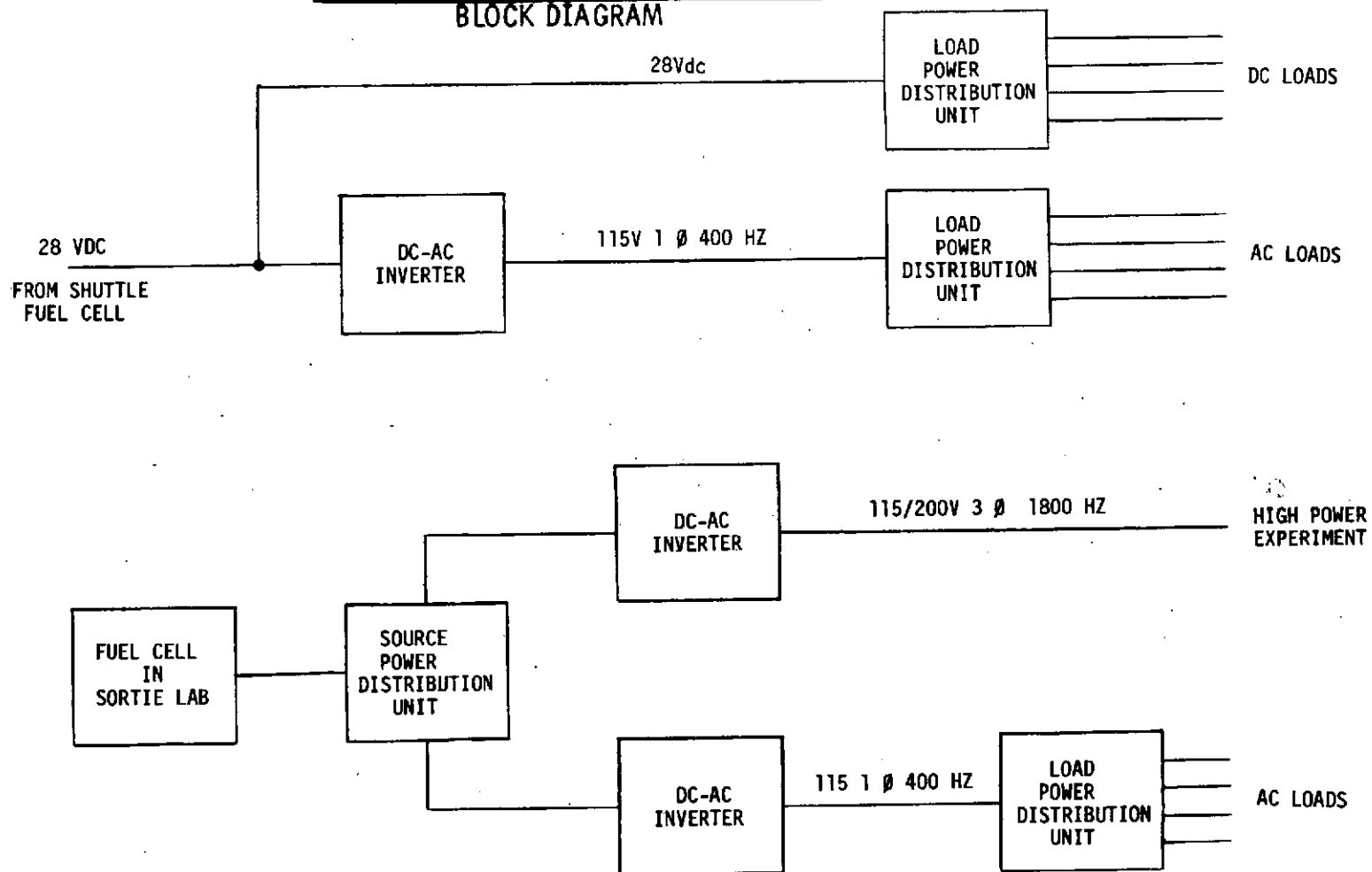


FIGURE 9

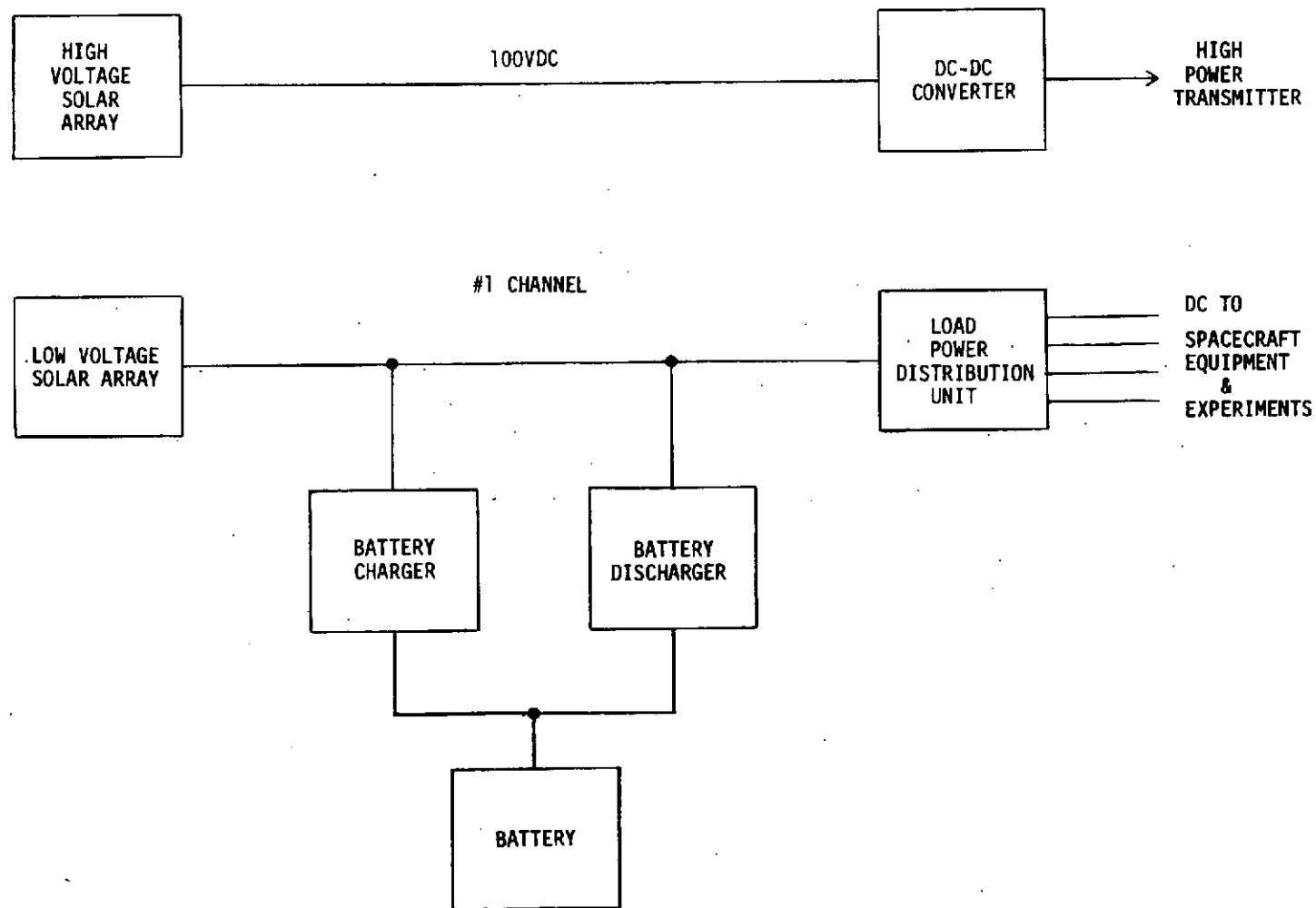
Figure 10 illustrates the power processing system for a synchronous satellite. It includes both a high voltage array to operate high power transmitting equipment, and a low voltage solar array to supply power for the standard spacecraft equipment and experiments. To improve the basic reliability of the satellite, it is anticipated that a completely redundant power system identical to Channel #1 would be used. The low voltage system also includes the storage battery to operate the spacecraft during launch, transient operating modes and eclipse operation.

11.3.5 Planetary Satellite System Block Diagram

Many exploratory satellites are being planned to observe other planets in our solar system, comets and space beyond our solar system. It is extremely important that the cost of these satellites be minimized to allow a full collection of data to determine the nature of our solar system and the nature of our planet.

Figure 11 illustrates the power processing system planned for the planetary satellite programs. It includes a high voltage solar array to operate ion engines for electric thrust which minimize the flight time of the satellite. As the spacecraft flies away from the sun, the output power decreases due to the loss of illumination, therefore the power processing requires the throttling of the ion engines, by turning off ion engines or by changing the beam current to match available solar array power. As the spacecraft is further away from the sun, the solar array temperature decreases causing the operating potential of the solar array to increase. Thus, the high voltage solar array is constantly changing its power level and operating voltage as it flies away from the sun, and therefore requires the power processor to provide a load matching between the ion engine and the high voltage solar array.

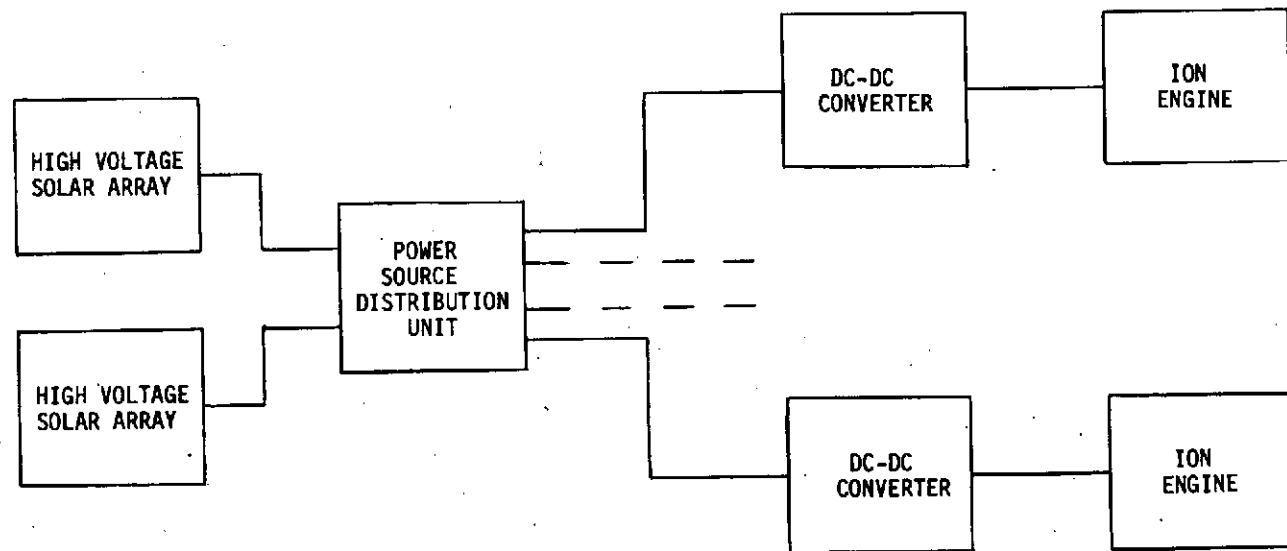
EARTH ORBIT SATELLITE POWER PROCESSING SYSTEM BLOCK DIAGRAM



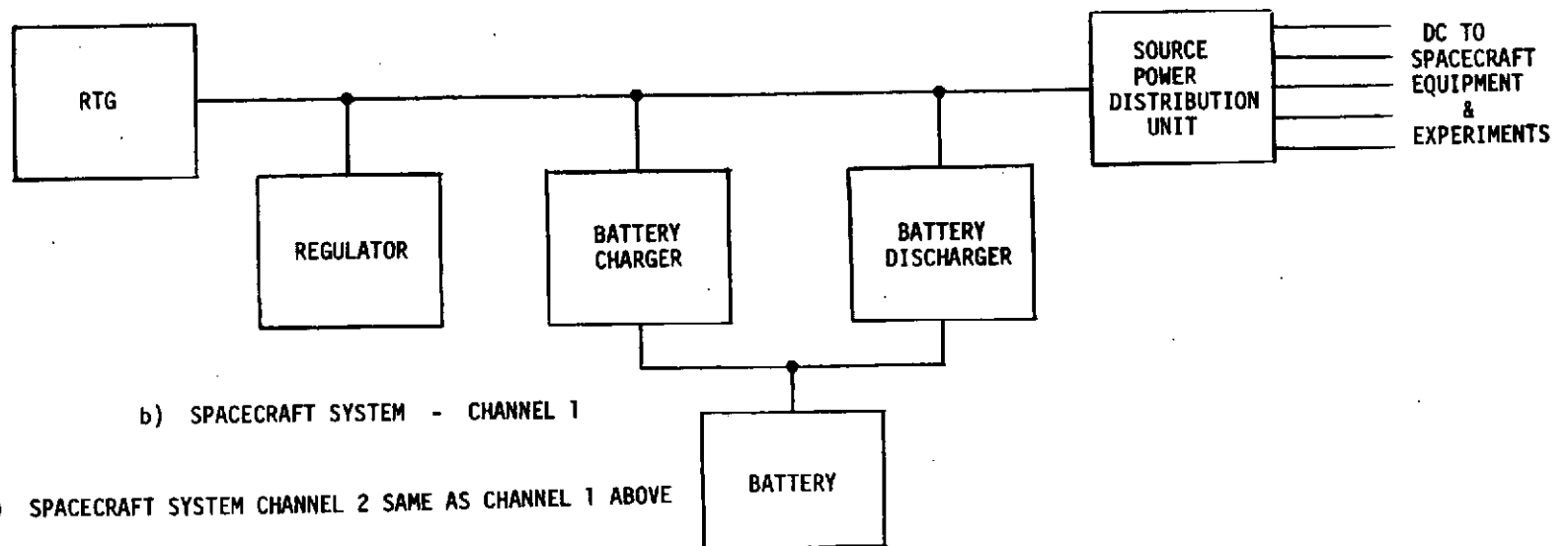
CHANNEL #2 SAME AS #1 CHANNEL ABOVE

FIGURE 10

PLANETARY SATELLITE POWER PROCESSING SYSTEM BLOCK DIAGRAM



a) ELECTRIC PROPULSION SYSTEM



b) SPACECRAFT SYSTEM - CHANNEL 1

c) SPACECRAFT SYSTEM CHANNEL 2 SAME AS CHANNEL 1 ABOVE

FIGURE 11

An RTG is used to supply the power to spacecraft equipment and experiments. The storage battery is used to handle peak transient conditions during abnormal operating modes of the equipment.

To improve the reliability of the power processing system, redundant RTG units and power processing systems are used, as shown in Figure 11.

In some instances, the RTG could be eliminated and the high voltage solar array bus could be conditioned to satisfy the voltage requirements for the spacecraft equipment and experiments.

In applications where electric propulsion is not required, this model can be modified for the new spacecraft design.

11.3.6 Military Aircraft System Block Diagram

Aircraft includes elaborate power processing systems which can be modeled in a fashion similar to the shuttle and satellites studied earlier. Because of this commonality of equipment, this modeling and analysis program will benefit the aircraft power system designer.

Figure 12 illustrates the power processing system for a military aircraft where there were four 3-phase 400 Hertz engine generators, each engine generator feeding an elaborate system with load distribution control centers. Tie breakers are used to cross-strap the engine generators in case of an engine generator failure.

An auxiliary power unit (APU) is used for startup of the aircraft and during emergency operation. An emergency battery is also used to supply critical loads during abnormal conditions of the ac engine generator system.

This basic power processing system can be used to model other aircraft power processing systems such as small military, commercial and small private aircraft.

MILITARY AIRCRAFT POWER PROCESSING SYSTEM **BLOCK DIAGRAM**

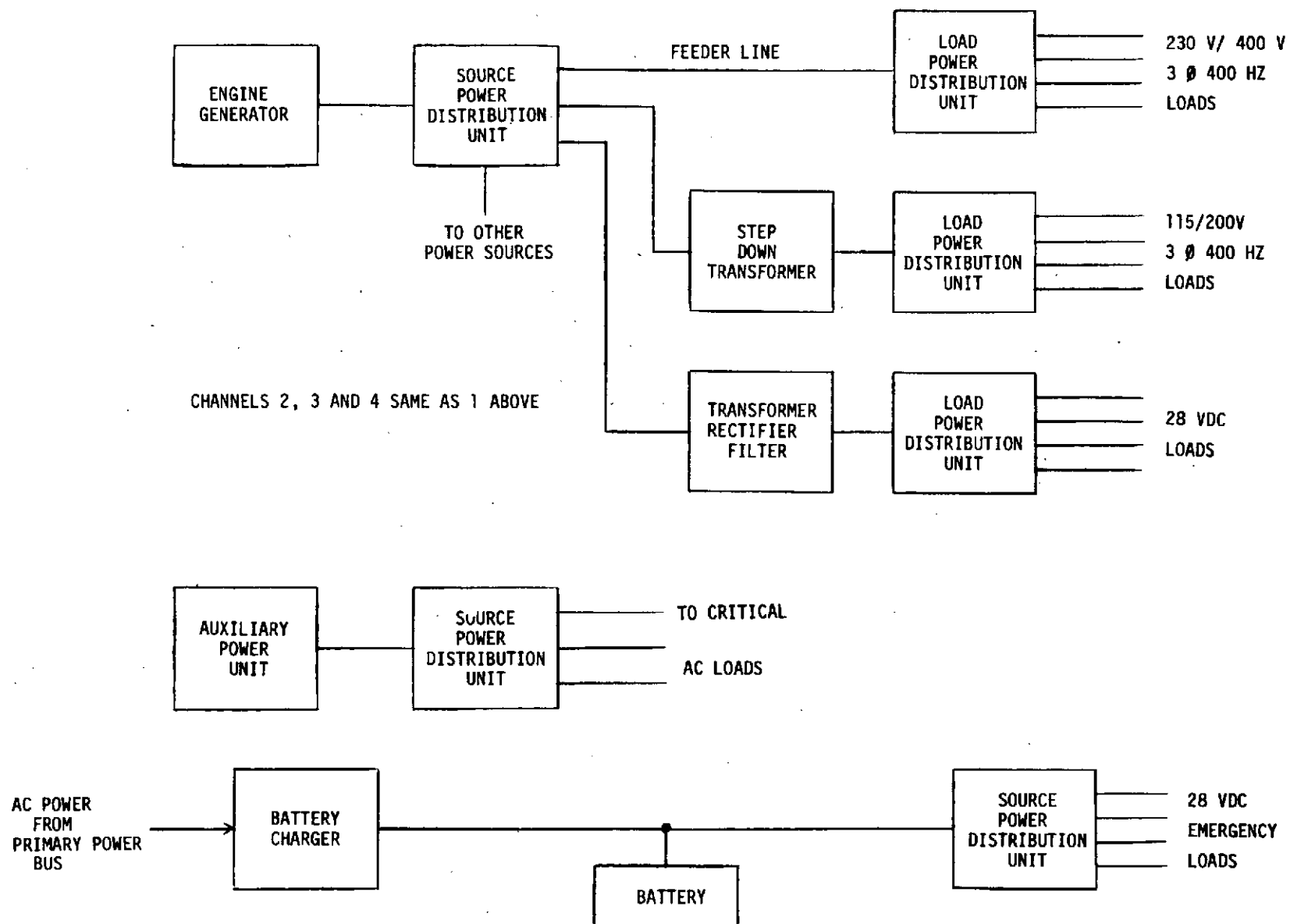


FIGURE 12

11.3.7 Equipment List for Five Selected Power Processing Systems

A preliminary power processing equipment list was generated for the five selected power processing systems for the Modeling and Analysis study. These programs include Space Shuttle, Sortie Laboratory, Synchronous Communications Satellite, Planetary Spacecraft and Military Aircraft.

Since these programs are in the initial planning stage, exact design specifications do not exist. This list identifies the basic classification of power processing equipment that must be studied in order to model the complete power processing system.

Shuttle. Table 7 summarizes the shuttle power processing equipment list according to the five subsystems---avionics, propulsion, environmental control, power control and distribution and payload.

Under the avionic system are included: (1) guidance and navigation, flight control, data management, data storage, communications, and display. The different power processing equipment have been identified for each section of the avionics system. Additional data is required to establish both the power level and operating voltage required from the power processing equipment and from the unregulated power processing bus.

In order to design and optimize power processing systems, it is required to know the total power distribution loads, both unregulated and regulated.

The propulsion system includes the equipment necessary to control and monitor the operation of the main propulsion engines, auxiliary propulsion unit, and air-breathing engines during final flight and landing.

The environmental control system includes not only the control of the air temperature for the astronauts, but also the environmental control for all equipment and the fire detection system.

TABLE 7

SHUTTLE POWER PROCESSING EQUIPMENT LISTA. Avionics Subsystem

Guidance and Navigation DC-DC Converter
 " " DC-AC Inverter

Flight Control DC-DC Converter
 " " DC-AC Inverter

Data Management DC-DC Converter

Communication DC-DC Converter

Display DC-DC Converter

B. Propulsion Subsystem

Main Propulsion Engine DC-DC Converter
 " " DC-AC Inverter

Auxiliary Propulsion System DC-DC Converter
 " " DC-AC Inverter

Air Breathing Engine System DC-DC Converter
 " " DC-AC Inverter

C. Environmental Control Subsystem

Environmental Control System DC-AC Inverter
 " " DC-DC Converter

D. Power Control & Distribution Subsystem

Auxiliary Power Unit DC-DC Converter
 " " DC-AC Inverter

Fuel Cell DC-DC Converter
 " " DC-AC Inverter

Load Distribution Unit DC-DC Converter
 " " DC-AC Inverter

The power control and distribution system includes the necessary controls for the fuel cell, auxiliary power unit, emergency battery, source control and power distribution unit, and load power and distribution unit. There is an additional subsystem in the shuttle payload area which may take on many different formats and cannot be generalized at this time other than it provides a power capability in the payload area.

Sortie Laboratory. Table 8 lists the equipment planned for the space laboratory. The subsystems are grouped into avionics, environmental control, power control and distribution system, and experiments.

The avionics subsystem is simplified over that of the shuttle. It provides a data management system, communications with the shuttle, and a display in the space lab.

Environmental control is required for controlling the ambient in the space lab. area and controlling the temperatures of the equipment.

The power control and distribution subsystem is different from the other systems that have been reviewed. A fuel cell power is inverted into either 400 Hertz or 3-phase 1800 Hertz for distribution throughout the space lab to reduce cable weight and to minimize the wiring problems when working with power levels up to 30kW. There will be a need for modularization of the dc to ac inverter systems in order to obtain the required power level.

The experiment subsystem is not clearly defined at this time other than it will use existing equipment designs converted to 400 Hertz operation for the low power scientific experiments. With high power equipment, redesign may be required to control the temperature in the space lab. area and its effects on the thermal control system.

TABLE 8

SORTIE LAB POWER PROCESSING EQUIPMENT LIST

A. Avionics Subsystem

Data Management DC-DC Converter
Communication DC-DC Converter
Display DC-DC Converter

B. Environmental Control System

DC-DC Converter
DC-AC Inverter

C. Power Control & Distribution Subsystem

Fuel Cell DC-DC Converter
" " DC-AC Inverter
Low Power Experiments Bus DC-AC Inverter
High Power Experiment Bus EC-AC Inverter

D. Experiment Subsystem

Low Power AC-DC Converters
High Power AC-DC Converters

Synchronous Satellite. Table 9 summarizes the equipment lists used on the synchronous satellite. Again, it is divided into the basic subsystem categories of avionics, propulsion, environmental control, power control, distribution and payload.

The avionics subsystem provides tracking, telemetry and command, the lower power communications, and attitude and control. It is also possible that some data management and data storage could also be available.

The propulsion subsystem includes the stationkeeping ion engine.

The environmental control system provides the necessary heaters to control the environment for equipment during launch and eclipse operation where undue low temperature could cause equipment failures.

Power control distribution subsystems include solar array regulator controls, battery chargers, batteries, and the source power control and distribution system. Because of the small size of these satellites, there may not be a need for separate load power control or distribution system.

The payload subsystem for the synchronous satellite could include low power TWT's which in turn drive high power TWT's for direct broadcast applications.

In near-earth orbit applications, the payload system could include elaborate television cameras and sensors for observation of the earth or observation of the sun.

This model for the earth orbit satellite can be easily modified to suit various military programs.

TABLE 9

EARTH ORBIT SATELLITE POWER PROCESSING EQUIPMENT LIST

A. Avionics Subsystem

Tracking Telemetry/Command DC-DC Converter
Communications DC-DC Converter
Attitude Control DC-DC Converter
Attitude Control DC-AC Inverter

B. Propulsion Subsystem

Station Keeping Ion Engine DC-DC Converter

C. Power Control & Distribution Subsystem

Solar Array Shunt Regulator (DC Regulator)
Battery Charger (DC Regulator)
Battery Discharge Regulator (DC Line Regulator)

D. Payload Subsystem

Low Power TWT DC-DC Converter (22-33Vdc Input)
High Power TWT DC-DC Converter (50-100Vdc Input)

Planetary Satellite. Table 10 illustrates the equipment list for the planetary satellite power processing system. It is divided into the major subsystems of avionics, propulsion, environmental control, power control, distribution, and experiment subsystems. This equipment list is very similar to that developed in Table 9 for the synchronous satellite, with the exception of the high power ion engine which must operate from a 200 to 400Vdc input.

TABLE 10
PLANETARY SATELLITE POWER PROCESSING EQUIPMENT LIST

A. Avionic Subsystem

Tracking Telemetry/Command DC-DC Converter
Communication DC-DC Converter
Medium Power TWT DC-DC Converter
Attitude Control DC-DC Converter
Attitude Control DC-AC Inverter
Data Storage Unit DC-DC Converter
Data Management DC-DC Converter

B. Propulsion Subsystem

Ion Engine DC-DC Converter (200-400Vdc Input)

C. Environmental Control

D. Power Control & Distribution System

RTG Shunt Regulator (DC Line Regulator)
Battery Charger (DC Regulator)
Battery Discharge Regulator (DC Line Regulator)

E. Experiment Subsystem

Experiment DC-DC Converter

Military Aircraft. Table 11 lists the power processing equipment used in a military aircraft such as the B1 which is in development now. It is grouped into the basic subsystems such as: avionics, propulsion, environmental control, power control and distribution, and payload.

The avionics system is somewhat similar to the avionics system used in the shuttle, only the propulsion system includes the air-breathing jet engines.

The environmental control system controls the environment for the pilot, the aircraft, and the electronic equipment.

The power control and distribution subsystem controls the output of the engine generators, auxiliary power unit, and the battery charger for the emergency battery.

The biggest difference between aircraft is in the payload. It may include a tactical electronic warfare system which is used for bombing, fire control, and jamming of enemy radar or weapons systems. The payload may also include a high power radar and its elaborate scanning system. The electronic countermeasure TWT's included in the payload are used to jam enemy tracking systems. A new subsystem under development is a laser that can be used for protection of the aircraft.

Here is a new set of power processing equipment requirements that have not been identified in the preceding power processing systems discussions.

TABLE 11

MILITARY AIRCRAFT POWER PROCESSING EQUIPMENT LIST

A. Avionics Subsystem

Guidance & Navigation AC-DC Converter
Guidance & Navigation AC-AC Inverter
Flight Control AC-DC Converter
Flight Control AC-AC Inverter
Communication AC-DC Converter
Data Management AC-DC Converter
Display AC-DC Converter

B. Propulsion Subsystem

Main Propulsion Engine AC-DC Converter

C. Environmental Control Subsystem

Environmental Control AC-DC Converter

D. Power Control & Distribution Subsystem

Main Engine Generator Controller
Auxiliary Power Unit Generator Controller
Battery Charger (AC-DC Regulator)

E. Payload Subsystem

Tactical Electronic Warfare System AC-DC Converter
Radar AC-DC Converter
Radar AC-AC Inverter
Electronic Countermeasure TWT AC-DC Converter
Laser AC-DC Converter

11.4 SOURCE/PPE/LOAD INTERACTIONS

In order to determine the interface requirements for the power processing equipment, it is necessary to determine the interactions between the loads, power processor, and power source. Any error in the specifications of these interactions can generate a penalty in the design of the power processing equipment or result in power processing equipment that will not fulfill requirements.

Table 12 summarizes the possible interacting parameters. Their interactions must be identified for each type of equipment and power sources of the five selected PPS's.

The variation of the load demand must be described in terms of the power and the frequency. Overload conditions, transients, or arcing must be identified so that adequate protection can be designed into the power processing equipment to protect itself and the power source.

Consideration of power source voltage transients affects the design of the power processing input filter and design of power processing regulation techniques. It is important to isolate these transients from being reflected to noise sensitive load equipment such as digital computer circuits.

TABLE 12

INTERACTIONS

Load Variation

Load Overloads/Transients

Power Processor Input Filtering

Power Processor Regulation Technique

Power Processor Switching Frequency

Power Processor Internal Protection

Power Processor Load Protection

Power Processor Reflected Current-Steady State

Power Processor Reflected Current-Transient

Power Source Impedance

Power Source Voltage Variation

Power Source Voltage Transients

The power processor input filtering must be controlled in that it can interact with the input filters on other equipment, the power source or the power processor itself due to the power processor's negative impedance.

The power processor regulation techniques also interact with the load, and the reflected current back into the power source. The regulation techniques used can greatly influence the performance of the power processing equipment during dynamic variation in the power source or load equipment.

The power processor switching frequency also has an interaction on the values of the input-output filters, the values of the ripple frequency on the output and the reflected current ripple frequency back into the power source. The switching frequency greatly influences the efficiency and weight characteristics of the power processing equipment.

Any power processing load protection used will also interact with the internal design techniques.

The power processor reflected current transient whether due to initial charge of the input filter, turn-on transients of the power processing equipment, or due to load shorts or transients, must be controlled to eliminate disturbance of the power source. This disturbance of the power source is reflected as an input disturbance to the remaining power processor equipment.

The power source impedance interacts with the power processing equipment in that it can disturb the resonant conditions of the input filters and acts as a coupling impedance between various power processing systems under load variations. These load variations cause a power source variation which can be either a low frequency transient or a high pulse transient. These variations can also be due to change in the power source capability due to either illumination variations, or overload conditions that cause collapse of the bus system.

11.5 DESIGN EQUATIONS TO ACHIEVE MINIMUM TOTAL WEIGHT OF MAGNETICS AND SOURCES

The weight optimization can no longer be limited to the magnetics alone if one wishes to minimize the combined weight of (1) the magnetics, and (2) the portion of the power-source weight necessary to supply the losses in the magnetics. Rather, there exists a conversion factor K relating the losses in magnetics to the additional source weight needed to supply these losses. One must therefore minimize [(magnetics weight) + K (loss in magnetics)], where K is estimated as 0.015kg/watt. In the following derivations, an inductor is used as an example for design.

Copper and Iron Losses

Let the rms current in the winding be I_{rms} , then, the copper loss P_c becomes:

$$P_c = I_{rms}^2 \rho \frac{4F_c N \sqrt{A}}{A_c} \quad (1)$$

where ρ is the resistivity in ohm-meter, A_c is the winding cross-sectional area in meter², $4F_c \sqrt{A}$ is the mean length per turn of the copper conductor in meter, and N is the number of turns.

The iron loss in joule/cycle corresponds to the area $\phi_m (2NI_o)$, where ϕ_m is the flux excursion, NI_o is the amp-turns required to magnetize the core. Since $NI_o = Hz$ and $\phi_m = B_m A$, where z is the mean length of magnetic path, and A is the cross-sectional area of the core, the energy loss per cycle becomes $2B_m H A z$. Consequently, the iron loss corresponding to an operating frequency F becomes

$$P_i = 2B_m H F A z \quad (2)$$

Total Source and Magnetics Weight

Using the aforementioned factor K , the additional source weight is

$$W_s = K \left(I_{rms}^2 \rho \frac{4F_c N \sqrt{A}}{A_c} + 2B_m H F A z \right) \quad (3)$$

Adding to this weight the weight of the magnetics, which is

$$W_m = 4F_c A_c D_c N \sqrt{A} + D_i A z, \text{ where } D_c \text{ and } D_i \text{ are copper and iron densities,} \quad (4)$$

the combined source and magnetics weight to be optimized becomes:

$$W_T = 4F_c D_c N \sqrt{A} A_c + D_i A z + K \left(I_{rms}^2 \rho \frac{4F_c N \sqrt{A}}{A_c} + 2B_m H F A z \right) \quad (5)$$

Optimization Approach

The total weight represented in Equation (5) is to be optimized based on the same two constraints concerning the inductance required and a window to be filled. These two constraints are:

$$NA = \frac{LI_p}{B_m} \quad (6)$$

$$\sqrt{\frac{A_c N}{\pi F_w}} - \frac{z}{2\pi} + \frac{\sqrt{A}}{2} = 0 \quad (7)$$

For simplification purpose, let

$$\begin{aligned} K_1 &= 4F_c D_c \\ K_2 &= D_i + 2KB_m HF \\ K_3 &= 4KI_{rms}^2 \rho F_c \\ K_4 &= LI_p / B_m \\ K_5 &= 1 / \sqrt{\pi F_w} \\ K_6 &= 1/2\pi \\ K_7 &= 1/2 \\ x &= \sqrt{A}, y = \sqrt{N}, v = \sqrt{A_c} \end{aligned} \quad (8)$$

Then, Equations (5) to (7) are reduced to:

$$W_T = K_1 x y^2 v^2 + K_2 x^2 z + \frac{K_3 y^2 x}{v^2} \quad (9)$$

$$x^2 y^2 - K_4 = 0 \quad (10)$$

$$K_5 y v - K_6 z + K_7 x = 0 \quad (11)$$

The optimization function $h(x, y, z, v)$ becomes:

$$h(x, y, z, v) = K_1 x y^2 v^2 + K_2 x^2 z + \frac{K_3 x y^2}{v^2} - \alpha (x^2 y^2 - K_4) - \beta (K_5 y v - K_6 z + K_7 x) \quad (12)$$

where α and β are the Lagrange Multipliers. Thus, in addition to the two equations given as Equations (10) and (11), one has the following four more equations:

$$\frac{\partial h}{\partial x} = 0, \quad \frac{\partial h}{\partial y} = 0, \quad \frac{\partial h}{\partial z} = 0, \quad \frac{\partial h}{\partial v} = 0$$

These six equations can be used to solve the six unknowns, x, y, z, v, α and β . A design based on these core and winding parameters represents the minimum combined magnetic and source weight. The optimum permeability μ can then be found from x, y, z , and the required inductance L through the identity $L = \mu N^2 A / z$.

The four aforedescribed partial differentiations yield:

$$\frac{\partial h}{\partial x} = K_1 y^2 v^2 + 2K_2 x z + \frac{K_3 y^2}{v^2} - 2\alpha x y^2 - \beta K_7 = 0 \quad (13)$$

$$\frac{\partial h}{\partial y} = 2K_1 x y v^2 + \frac{2K_3 x y}{v^2} - 2\alpha x^2 y - \beta K_5 v = 0 \quad (14)$$

$$\frac{\partial h}{\partial z} = K_2 x^2 + K_6 \beta = 0 \quad (15)$$

$$\frac{\partial h}{\partial v} = 2K_1 x y v - \frac{2K_3 x y}{v^3} - \beta K_5 = 0, \quad y \neq 0. \quad (16)$$

Optimization Results

By solving Equations (10) to (16), the following results can be obtained:

$$N = \left(\frac{L I_p \pi F_w}{A_c B_m} \right)^{1/2} S^{-1} \quad (17)$$

$$A = \left(\frac{L I_p A_c}{\pi B_m F_w} \right)^{1/2} S \quad (18)$$

$$Z = 2\pi \left(\frac{L I_p A_c}{\pi B_m F_w} \right)^{1/4} \left(\frac{S^{1/2}}{2} + S^{-1/2} \right) \quad (19)$$

$$A_c = \left(\frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \right)^{1/2}, \text{ choose } A_c < \sqrt{\frac{K I_{rms}^2 \rho}{D_c}} \quad (20)$$

$$\mu = 2\pi \left(\frac{B_m}{I_p} \right)^{5/4} \left(\frac{A_c}{\pi F_w} \right)^{3/4} L^{-1/4} S \left(\frac{S^{1/2}}{2} + S^{-1/2} \right) \quad (21)$$

$$S = \frac{4 F_c F_w \left(\frac{K I_{rms}^2 \rho}{A_c^2} - D_c \right)}{D_i + 2 K B_m H F} \quad (22)$$

Where

$$a = 3 D_c \left(4 F_c D_c - \frac{D_i + 2 K B_m H F}{F_w} \right) \quad (23)$$

$$b = K I_{rms}^2 \rho \left(\frac{D_i + 2 K B_m H F}{F_w} - 24 F_c D_c \right)$$

$$c = 12 (K I_{rms}^2 \rho)^2 F_c$$

Substituting these values for N, A, Z, and A_c with eq. (5), the minimum total weight $(W_T)_{min}$ of the magnetics and the source becomes

$$(W_T)_{min} = 2\pi \left(\frac{L I_p A_c}{\pi B_m F_w} \right)^{3/4} S^{-1/2} \left[2 F_c F_w \left(D_c + \frac{K I_{rms}^2 \rho}{A_c^2} \right) + (D_i + 2 K B_m H F) S \left(1 + \frac{S}{2} \right) \right] \quad (24)$$

The optimum design equations shown in this appendix are based on a toroid magnetic core configuration. However, they are easily modified to fit other physical configurations such as rectangular or double-E. The only change needed is for eq. (4) of this appendix, to reflect the new core geometry since eq. (4) is based on a toroid configuration with a square cross-section.

The same approach described herein, when applied to a transformer design using a square-loop B-H core, can lead to a set of optimum design equations. The equations are identical in form to those presented, except that the quantity LI_p is replaced by the volt-second content of the transformer design. The results thus obtained for a square-loop B-H transformer were successfully applied to the transformer design of the 2KW, 2KV ion-engine power conditioner. It was found from the design equations that the ferrite core, although seemingly superior in losses, actually produced a heavier total system weight when compared with another higher-loss material of larger flux-density.

A particular note of interest concerning these design equations is the fact that, once the inductance L and the peak current I_p are known, one can directly calculate the magnetics weight and for a given magnetic material the total system weight without actually performing any design on the inductor or the transformer itself. The advantage offered by this time-saving feature, particularly for a parametric study program, is obvious.

Conclusion

Equations specifying the core dimension, the permeability, the turns, and the conductor size are derived to facilitate a toroid inductor design leading to an overall minimum combined weight for the magnetics and the portion of the source necessary to supply the inductor losses. The designed inductor is one such that its window is essentially filled, and the magnetic capability of its core is fully utilized without reaching saturation.

Using this same method of Lagrange Multiplier, the same optimization procedures can be, and have been applied to other optimizations to include:

- The design of saturable rectangular-BH-loop transformers
- The design for both inductors and transformers under different optimizing constraints. These constraints include the minimum magnetics weight per se for a given loss, or the magnetics design yielding a minimum weight-loss product.

These advanced design procedures, often in closed expression form such as those presented herein and readily adaptable for digital computation, are believed to be ahead of the state-of-the-art in magnetics design.

Since a majority of the power-conditioning subsystem weight is caused by the power magnetics, the utility of a set of well-conceived optimum design equations will certainly contribute to the program objective of maximizing the power density of the spacecraft power system.

11.6 AN EXAMPLE OF PREVIOUS PARAMETRIC STUDY RESULTS

The example consists of parametric data for LC type of DC filtering. The following four cases are considered:

Case 1 - Small Alternating Current

An example is an input filter to a square wave inverter where no appreciable ac current or voltage is applied to the filter.

Case 2 - High Alternating Current

An example is an input filter in a switching bucking regulator where high ac current exists in the filter capacitor.

Case 3 - High Alternating Voltage

An example is an output filter in a switching bucking regulator where high ac voltage exists in the filter inductor and minimal ac current in the filter capacitor.

Case 4 - High Alternating Current and Voltage

An example is the output filter on a buck-boost switching regulator design where there is high ac voltage across the inductor and high ac current in the filter capacitor.

Parametric data on losses, weights, and failure rates have been computed for these functions over a voltage range of 30 to 300 volts. For this set of data, the switching frequency is assumed to be 10 KHz. The specified power and voltage ranges have been rearranged into a set of discrete function design points that effectively cover the desired ranges:

Output voltage	30, 100, and 300 Vdc
Power	1 KW, 3 KW, and 10 KW

The parametric data as developed from the analysis models generated is illustrated graphically in Figure 13 by four curves:

- Percentage loss versus operating voltage at a fixed power level
- Weight versus operating voltage at a fixed power level
- Failure rate versus operating voltage at a fixed power level
- Scaling constant curves for percentage loss, weight, and failure rate versus output power level at a constant voltage and frequency.

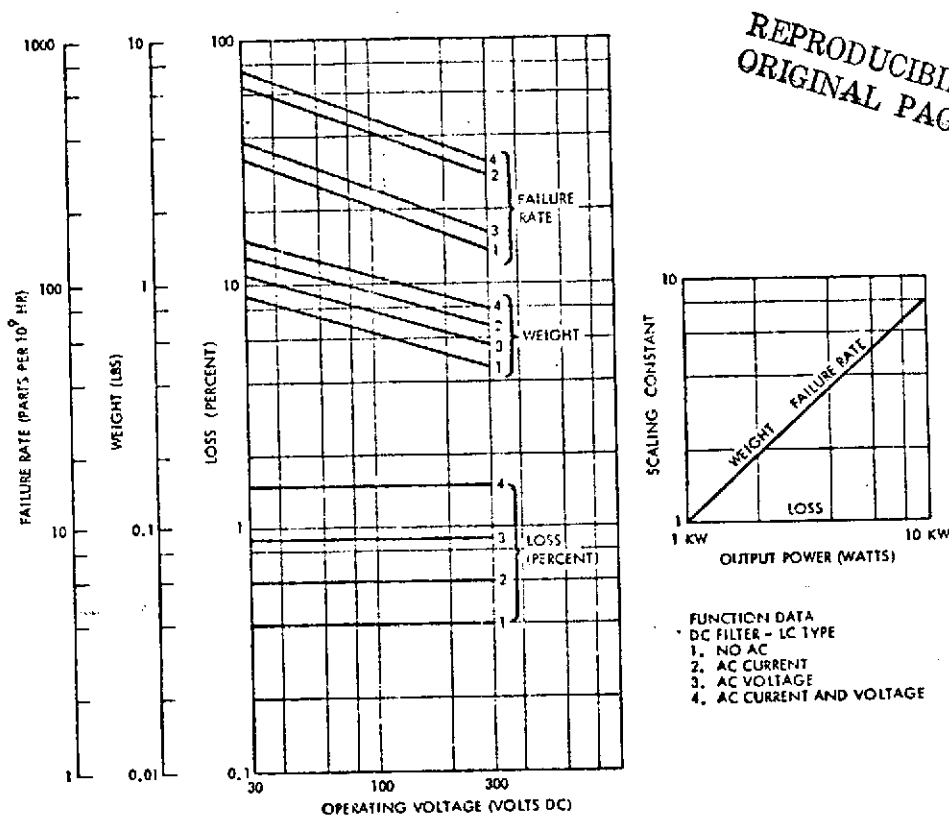


Figure 13 Function Data, DC Filter - LC Type

The percentage loss, weight, and failure rate are plotted as a function of operating voltages for a selected switching frequency and output level. The scaling constant curve allows the three curves of percentage loss, weight, and failure rate to be modified as a function of output power level. To use the scaling constants, the percentage loss, weight, and failure rate for a selected operating voltage and frequency are determined from the first three curves, which are plotted for a 1 KW design operating at 10 KHz. The scaling constant curves give the multiplying factors that are used to change the original data to the data at another power level.

Percentage loss here is defined as the ratio of the losses to the sum of losses and output power. This is selected rather than efficiency because it simplifies the analysis of relationships of individual functional losses to total power conditioner loss. Efficiency can be determined as one minus the percentage loss.

11.7 CUMULATIVE POWER PROCESSING FUNCTION PARAMETRIC DATA

The power functional design data characteristics are accumulated to determine the overall power conditioning equipment characteristic. Examples of parametric data from the final report of Contract NAS 7-546, "Analysis of Aerospace Power Conditioning Component Limitations," are presented in Figures 14, 15 and 16, for a switching buck-type line regulator. These data were generated in 1968 and 1969, and do not include up-to-date new component characteristics, new electrical design methods to reduce losses, and improved component failure rate. These figures illustrate the presentation of power conditioning parametric data and its analysis techniques.

These curves show, graphically, the cumulative effect of individual power functions on total power conditioner percentage loss, weight, and failure rate. The weight data given excludes the effect of signal level functions, packaging, cabling, and connectors, but includes the weight of semiconductor heat sinks for component thermal control. On Contract NAS5-21066, "20 KW Battery Study Program," techniques to include signal level functions and power conditioner packaging effects have been developed so that complete power conditioning parametric data can be accurately determined.

In the following paragraphs, the general nature of these results is described:

Percentage Loss. The loss curve (Figure 14) portrays total conditioner percentage loss as well as the cumulative contribution of individual functions at any particular switching frequency. The vertical distance between two curves at a selected frequency represents the percentage losses of a particular power function at that frequency. Additional minor losses due to the signal functions and power cabling are not shown. Power conditioner efficiency can be determined as one minus the percentage loss.

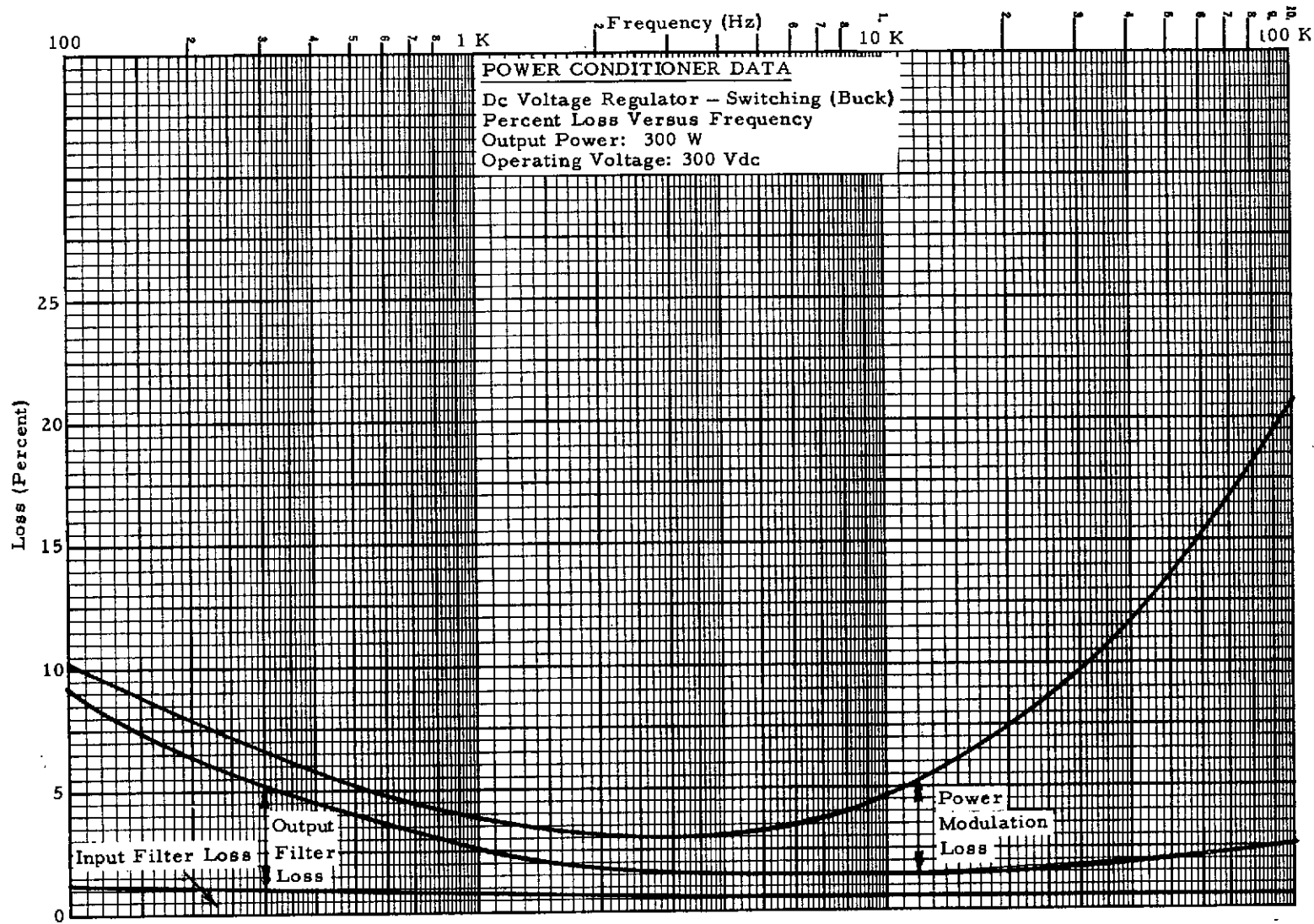


Figure 14. Power Conditioner Data, Dc Voltage Regulator

At low switching frequencies, the output filter losses were made large to reduce the weight of that function. This is a classical example of the interaction between weight and losses depending on the design techniques on the parametric function.

At high switching frequency, the switching characteristics greatly increase the losses in the power modulation function. New components with improved switching characteristics and the development of the energy recovery networks have greatly improved this characteristic.

When determining total loss, a slight error exists in accumulating the individual losses in this manner. Thus, when there are three functions with 1, 2, and 4% losses, respectively, the accumulated loss (as determined by taking the sum) is 7%, indicating a conditioner efficiency of 93%. Efficiency, as actually calculated; i.e., by multiplying individual efficiencies of each function, is $0.99 \times 0.98 \times 0.96 = 0.931$; thus, a net error of 0.1% efficiency exists in the former method. Despite the small error inherent in this method, losses in individual functions can be compared with each other, and the predominated ones are easily determined.

Weight. The weight graph (Figure 15) is also cumulative in that vertical distance between two curves at a selected frequency represents the percentage weight of a particular power function at that frequency. The graph shows the effect on power system weight due to the additional amount of primary power source required to supply losses in the power conditioner. The factor 0.6 lb/W is used for this computation since it represents the penalty involved with a typical power source configuration such as a solar array/battery to compensate for the losses in the total power conditioner. The data, as previously noted, do not include the weight of signal functions, mechanical packaging, cabling, or connectors. Since the generation of these data, functional data for signal functions and mechanical packaging have been determined and complete power conditioner weight can be more accurately determined.

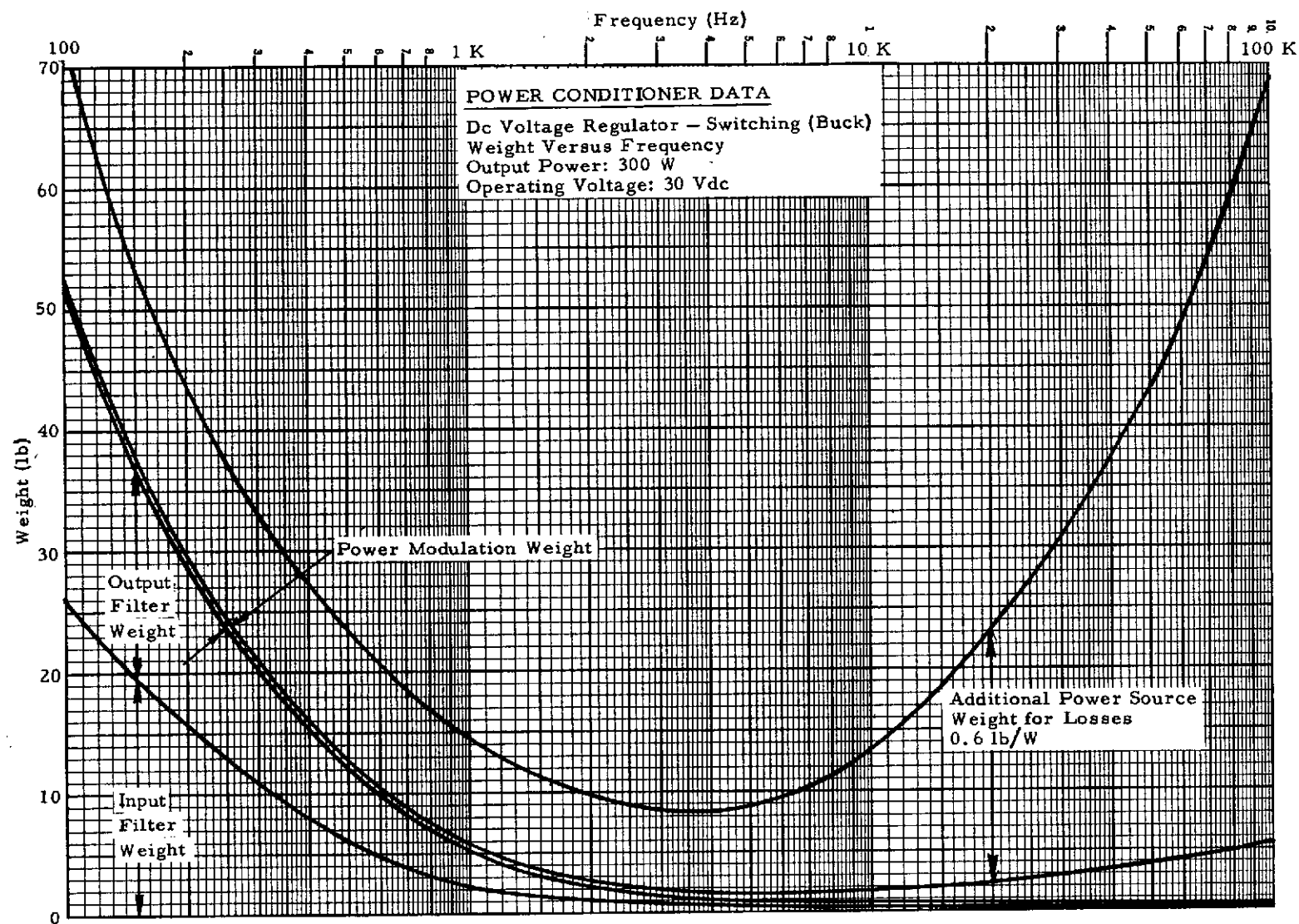


Figure 15 . Power Conditioner Data, Dc Voltage Regulator

In analyzing the data shown in Figure 15, both the input and output filter weights are large at the low switching frequencies due to the large size of the filtering elements.

At high frequencies, a slight weight penalty is incurred in the power modulation due to increased weight of the semiconductor heat sinks. Proper thermal design characteristics are required to achieve low failure rates for the semiconductor components. As described earlier, the use of the energy-recovery networks can significantly change the shape of this curve.

The additional weight of the power source at high switching frequencies is due to the increased losses in the power modulation function. Here, again, the interaction of losses and weight is seen in the equipment design.

Failure Rate. The failure rate curve (Figure 16) is a cumulative graph where the vertical distance between two curves at a selected frequency represents the failure rate for a particular power function at that frequency. It does not include the failure rate of signal functions.

At low switching frequencies, both the input and output filter failure rates are high due to a large number of parallel capacitors necessary to obtain the total capacitance value.

Failure rate data and component derating factors must be standardized in order to obtain meaningful reliability calculations for the total power system.

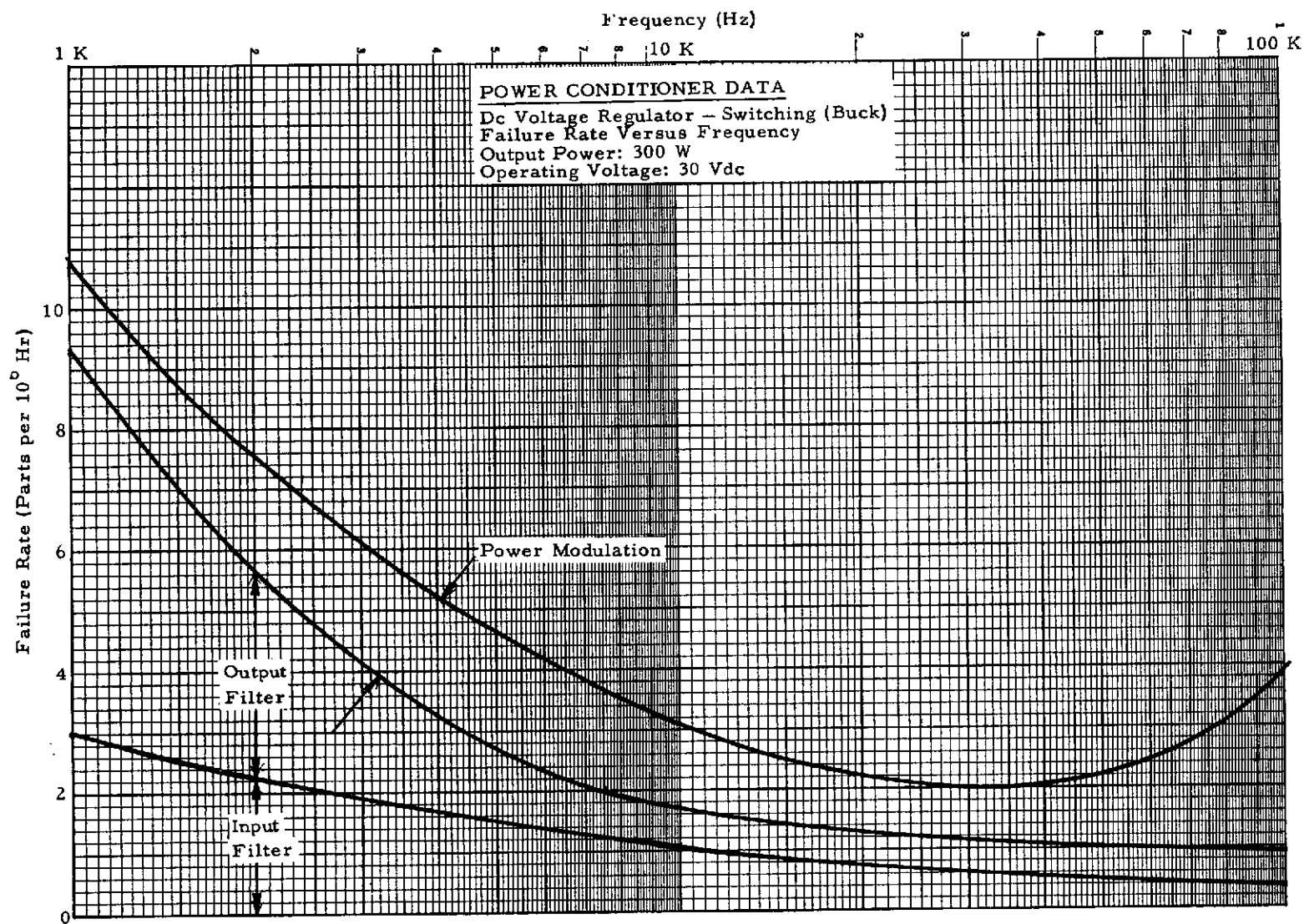


Figure 16 . Power Conditioner Data, Dc Voltage Regulator

11.8 EXISTING CONTROL MODE, CONTROL MECHANISM AND MODULATION PHILOSOPHIES

A power processing system embodies disciplines from several fields. A DC-to-DC converter-regulator, for example, contains a feedback loop closed around a DC amplifier, and its properties and design, therefore, involve those of the distinct fields of DC amplifiers and feedback amplifiers or servomechanisms. In many cases, the converter-regulator may be required to have a low output impedance up to frequencies in the megahertz range, and so the system also incorporates the problems of video amplifiers. Finally, and most significantly, the system incorporates ideally-lossless switching processes which introduce inherent nonlinearities into the processing functions. In general, therefore, a power processing system is a nonlinear DC to video frequency control system.

The literature of power processing systems pertaining to these various subfields is potentially teeming with significant analysis and modeling efforts. The literature survey has shown, however, that there has been very little attempt at synthesis of the numerous analysis and design approaches as applied to the special problems of power processing systems. There are two principal reasons for this:

(1) established analytical methods are rather sharply divided into linear and nonlinear techniques, and the nonlinear techniques usually apply to a particular type of nonlinearity, namely a hysteretic switch, which is only one of several switching concepts employed in power processing systems; (2) device modeling and circuit analysis techniques for switching-mode functions are usually directed towards low-power digital applications in which the available elements are switches, resistors, and capacitors; in contrast, in power processing systems, the available elements are switches, inductors, and capacitors, for which the entire design philosophy and modeling and analysis techniques are different.

In the absence of established and accepted catalogs of design concepts and analysis techniques, workers in the power processing field tend to adopt an arbitrary design concept to meet specific system requirements, usually, it seems, determined primarily by previous experience and familiarity with the chosen concept rather than by any more objective criteria concerning the "best" approach. The same is true with regard to choice of analytic technique. The present status of the field, therefore, is that of a number of conceptual implementations and a number of analytical techniques available, each has been partially developed, but with no comparative information. A survey of these follows:

11.8.1 System Configurations

Single-Loop Switching Regulators

The essential elements of a single-loop regulator are shown in Figure 17. The inherent nonlinear functions are contained in the Modulator and Power Stage, in which the Modulator converts an analog signal into a form of digital signal which in turn operates a controlled sampling switch in the power stage. The analog signal recovered by the low-pass filter constitutes the DC output.

Although control of the DC output is always affected via the ON/OFF duty ratio of the sampling switch, there are two possible classes of control mode, one of which has several subclasses:

1. Timing Reference
 - a. Constant T_{ON}
 - b. Constant T_{OFF}
 - c. Constant $T_S = T_{ON} + T_{OFF}$ (clocked, driven)
 - d. Constant product of input voltage E_i and T_{ON} ,
i.e., constant $E_i T_{ON}$.

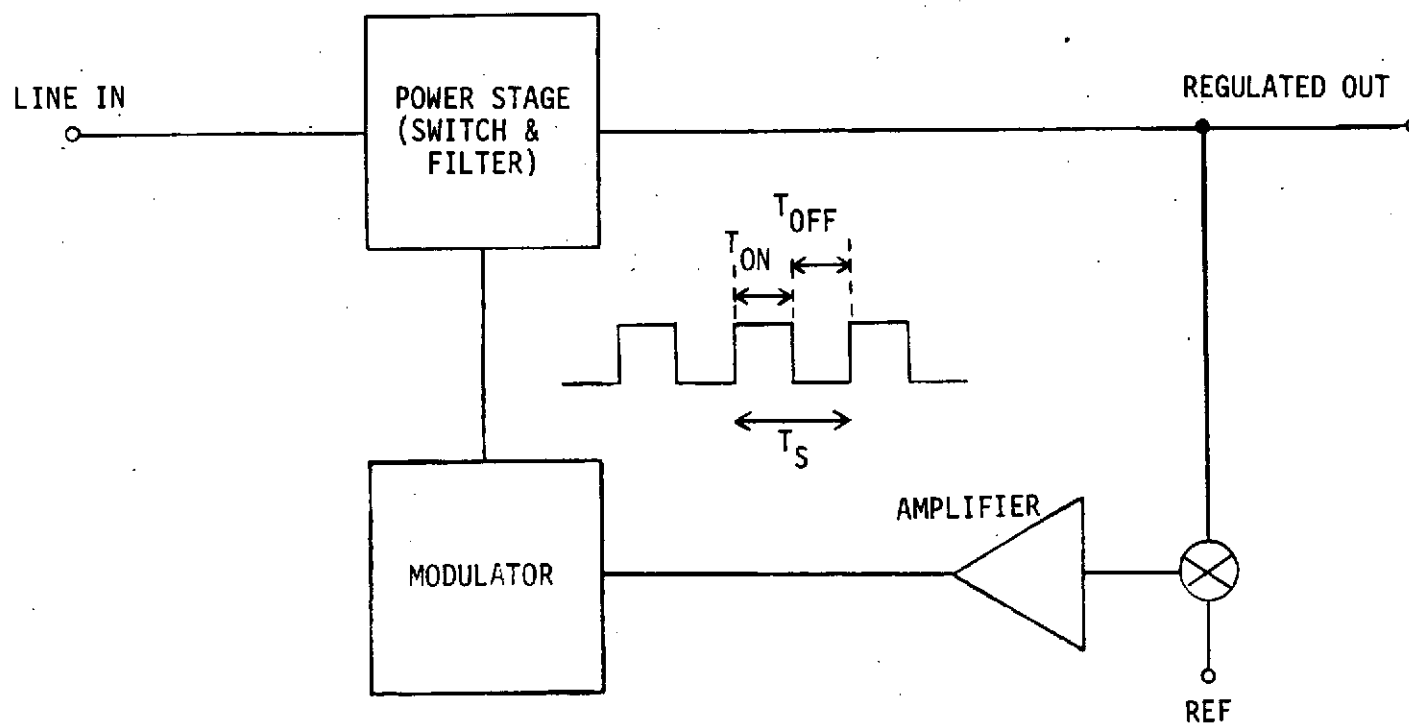


Figure 17. TYPICAL SINGLE-LOOP SWITCHING REGULATOR

2. Free-running (constant ripple, limit cycle, bang-bang)

The T_{ON} and T_{OFF} refer to the ON and OFF times of the sampling switch, and T_S is the switching period.

There are two possible classes of power stage configuration:

1. Buck (chopper)
2. Boost (flyback)

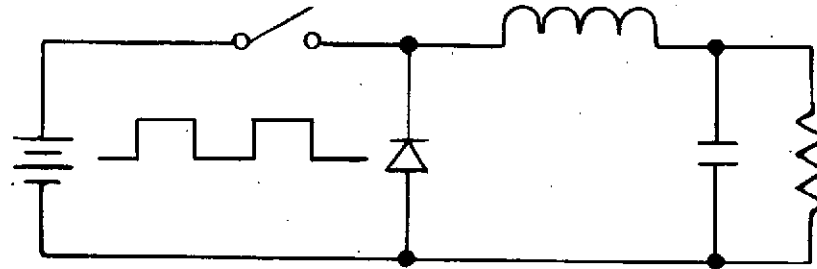
These are shown in Figure 18. The buck-boost configuration, with respect to its signal transmission round the feedback loop, is topologically the same as the boost configuration. There are numerous modifications of each of these classes, including symmetric push-pull switches, use of coupling transformers, and use of tapped inductors; however, the modeling of these modifications involves only simple scaling of the properties of the basic class.

The function of the Modulator is to convert an analog amplified error signal into a related time interval. This functional relation can be of four types:

1. Non-integrating explicit
2. Non-integrating implicit
3. Integrating explicit
4. Integrating implicit

In the non-integrating types, the timing interval is determined by an instantaneous sample of the error signal; in the integrating types, the timing interval is determined by the integral of the error signal over some previous period. In the explicit

1. BUCK (CHOPPER)



2. BOOST (FLYBACK)

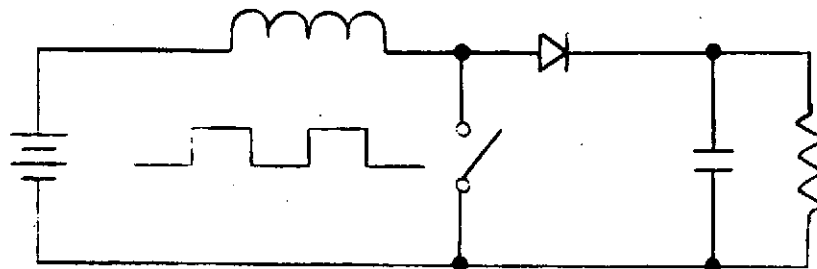


Figure 18. CLASSES OF POWER STAGE CONFIGURATION

types, the timing interval is determined explicitly by the value of the error signal at a known instant or by its integral over a known period, and in the implicit types, the timing interval is implicitly determined by the instant at which the instantaneous error signal or its integral reaches a given value.

Two-Loop Switching Regulators

A two-loop switching regulator contains an "outer" loop in which the output voltage is regulated, as in Figure 17, and an additional "inner" loop in which a different quantity of the Power Stage is also sensed and fed into the Modulator. While two-loop systems are not widely known, three types have been extensively developed, each of which is associated with a particular organization:

1. NASA/TRW ("ASDTIC") (Figure 19).
2. Bose Corp. (Figure 20).
3. Hewlett-Packard Co. (Figure 21).

In the NASA/TRW system^[26, 31], the inner loop senses voltage across the filter inductor, integrates it, and combines it with the error signal of the outer loop. The inner loop essentially senses the instantaneous AC current in the filter inductor. In the Bose System^[18, 32], the filter inductor current is directly sensed and combined with the outer loop error signal in the Modulator. The principal difference in the two systems is that in the Bose System, the inner loop frequency response extends down to DC. In the Hewlett-Packard System^[33], the filter is in two cascaded sections, and the inner loop senses the output voltage between the two sections.

The variety of functional implementations listed under single-loop systems is also available in two-loop systems.

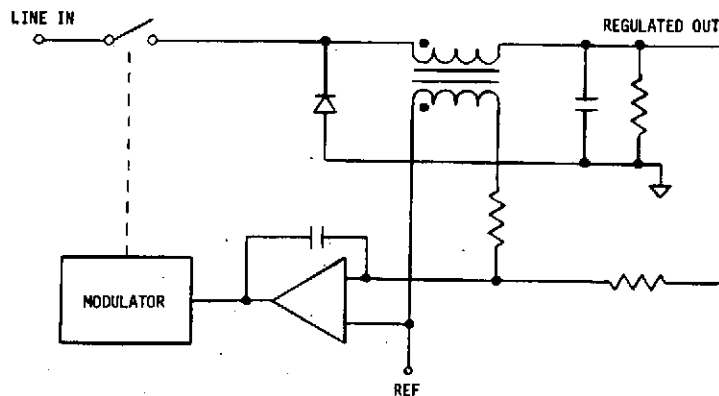


Figure 19. TWO-LOOP SWITCHING REGULATORS
(1) NASA/TRW (ASDTIC)

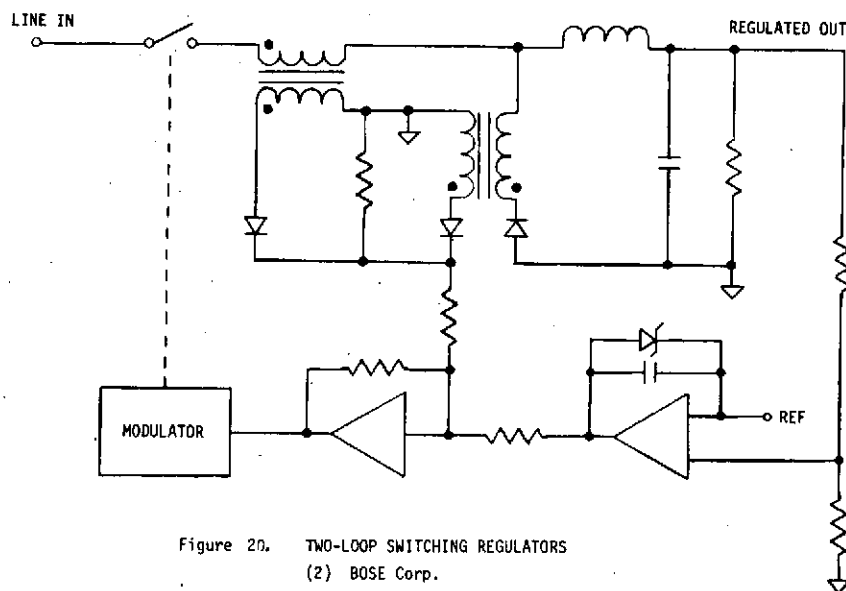


Figure 20. TWO-LOOP SWITCHING REGULATORS
(2) BOSE Corp.

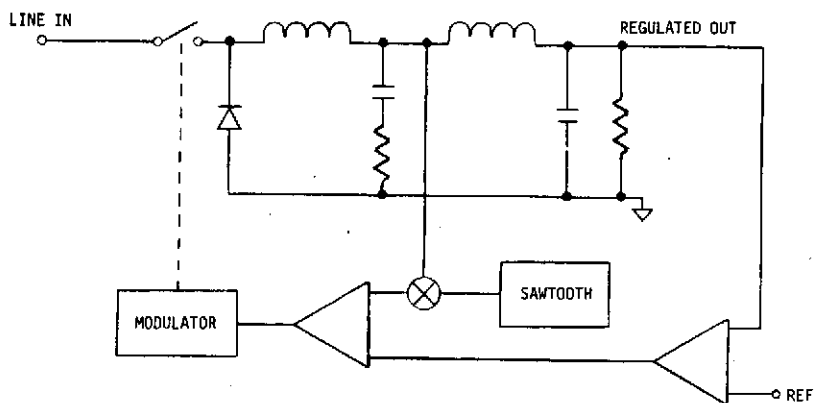


Figure 21. TWO-LOOP SWITCHING REGULATORS
(3) Hewlett-Packard

Two-Loop Switching Regulators

11.9 POWER PROCESSING EQUIPMENT PERFORMANCE ANALYSIS METHODS

There exists a variety of methods applicable to power processing equipment performance analysis. The techniques to be considered, and their merits and disadvantages, are summarized.

11.9.1 Applicable Analytical Methods

The methods include the following major categories:

(1) Frequency Domain Linearization Techniques

- Sample Data Z-Transform
- Describing Function

(2) Time Domain Discrete Model:

(3) Computer Simulation

- Digital: TESS (TRW Extended Sceptre Software)
CSM/O/P (IBM Continuous System Modeling and Optimization Program)
- Analog

11.9.2 Discussion on Different Analysis Techniques

The describing-function analysis requires that harmonics of the output of the nonlinear element are neglected. In the case of a dc to dc power processing equipment, the relatively low frequency of the output filter as compared to the switching frequency helps to provide a valid reason that generally holds this assumption true. Consequently, performance and oscillation stability can be examined both conceptually [34] and experimentally [35] by injection of a "test" signal into the loop, from which the loop gain as a function of complex frequency is determined. The large body of linear system theory is then applicable, including Bode and Nyquist plots, root-locus techniques, sensitivity relations, and Nyquist stability criteria. However, the accuracy deteriorates as the frequency approaches the switching frequency, and there is a special case when the test frequency is one half the switching frequency. Consideration of this special case illuminates the possible instability at the second subharmonic of the switching frequency. A more complex and less versatile quasi-linear technique employs

the z-transform method of sampled-data systems. The method is also based upon the assumption of a single-frequency test sinusoid, and becomes considerably more complicated when the switching frequency is not constant. Also, this method gives information only at the sampling instants. Nevertheless, even though system response is incompletely known, system stability may in some cases be more completely investigated than by the DF method.

The time-domain discrete model treats the control circuit during the on time and off time intervals as piecewise linear. Within each piecewise region, differential or algebraic equations can be formulated and their boundary conditions matched during the transitions between the on time and the off time. Solutions showing the control-system behavior can then be obtained, either explicitly or graphically, and the nature of the solutions examined to determine whether a limit cycle exists and what will be the transient response. The time-domain analysis possesses the advantages of more accuracy and large nonlinearity accommodation. However, due to perhaps power processing designer's preoccupation with the frequency-oriented performance characteristics (e.g., output impedance, etc.), the time-domain analysis has largely been limited to first and second-order system with a bistable hysteretic trigger.

Computer simulation is powerful in verifying results obtained through other analytical means. Both analog and digital computers are capable of performing the power processing equipment simulation, with the digital computer enjoying a greater accessibility and easier technology transmittal.

11.9.3 A Summary of Merits and Disadvantages of Various Method Analysis

The merits and disadvantages of the methods listed previously are summarized on Table 13. This table will serve as the guidelines in selecting the analysis approaches during phase B of the program.

Table 13 A Summary of Merits and Disadvantages for Various Methods of Analysis

Categories	Methods	Merits	Disadvantages	Remarks
Frequency Domain Linearization	Samples Data Z-Transform	<ul style="list-style-type: none"> Does not limit to second-order systems. Design Engineer's familiarity with linear system makes these techniques easier to communicate. Analytical results obtained are directly applicable for design optimization. 	<ul style="list-style-type: none"> More involved when the converter switching frequency is not constant. [10] Based on assumption of single-frequency sinusoid. 	Has applied to two-loop control analysis, with favorable results.
	Describing Function		<ul style="list-style-type: none"> System responses to inputs other than sinusoidal are not readily evaluated. Limited to only one nonlinearity. 	Certain nonlinearities (e.g., hysteresis) describing function are magnitude and frequency sensitive, giving a family of Bode Plots rather than a single frequency response curve.
	Low-Frequency Characterization		<ul style="list-style-type: none"> Based on assumption of single-frequency sinusoid. 	Accuracy is satisfactory for signal frequencies less than 10% of switching frequency.
Time Domain Analysis	Mathematical Analysis	<ul style="list-style-type: none"> Exact solution. Does not limit to second-order system. 	<ul style="list-style-type: none"> Less familiarity on the part of the design engineers 	One approach used successfully in spacecraft control is applicable.
	Graphical Analysis (Phase Plane)	<ul style="list-style-type: none"> Can accommodate large nonlinearity. 	<ul style="list-style-type: none"> Applications to systems higher than second order become very much involved. Cannot take sinusoidal forcing function. 	Application to power processor analysis has been limited to chopper using hysteresis control.
Computer Simulation	Digital	<ul style="list-style-type: none"> Easy to use. Great accessibility. 	<ul style="list-style-type: none"> May require long calculation time than analog Insight gained is not easily related to causes if applied without a mathematical analysis. 	There are programs that can take actual circuit topology and Fortran input routine.
	Analog	<ul style="list-style-type: none"> Shorter calculation time than digital computer. 	<ul style="list-style-type: none"> Need to write control-system differential equation. 	Has applied to two-loop control analysis, with favorable results.

11.10 AVAILABLE COMPUTER PROGRAMS FOR SYSTEM/EQUIPMENT DESIGN, ANALYSIS, AND OPTIMIZATION

Various computer programs are available for the analysis and simulation of electronic circuits and are briefly discussed in the following section.

11.10.1 TESS

The TRW Engineering System Simulator (TESS) is a digital computer program developed to perform large scale, nonlinear circuit and system analysis and design, and is a modification of the SCEPTRE program. A new program from IBM, CSM/O/P, provides the same basic capability. The TESS performs transient, DC and AC analysis through the use of three subprograms (TESS-TR, TESS-DC and TESS-AC). A system analysis capability is provided by the ability to input problems in terms of first order differential equations and state space formulation. The program is therefore applicable to electronic circuits as well as any system that can be represented by a set of coupled linear or nonlinear differential equations.

The program has the capability to analyze networks containing up to 601 nodes and 600 elements. Extensive use of "state-of-the-art" programming techniques, sophisticated list-processing techniques and sparse matrix schemes allow rapid analysis of large problems with minimum memory core usage. The program has a flexible user oriented input language common to all three subprograms and nearly identical to the input language of SCEPTRE (System for Circuit Evaluation and Prediction of Transient Radiation Effects). This general input language allows the use of equations, tabular data, defined parameters and FORTRAN function subroutines to define problems in both circuit and system analysis.

11.10.2 ECAP

The Electronic Circuit Analysis Program (ECAP) is an integrated system of programs designed to aid the electrical engineer in the design and analysis of electronic circuits. This system of programs can produce DC, AC, and/or transient analysis of electrical networks from a description of the connections of the network (the circuit topology), a list of corresponding circuit element values, a selection of the type of analysis desired, a description of the circuit excitation, and a list of the output desired.

ECAP recognizes a set of standard electrical circuit elements -- resistors, capacitors, inductors, independent current and voltage sources, mutual inductances, switches, and dependent current sources. Any electrical network that can be constructed from any or all of the different elements in the set can be analyzed by ECAP. There is almost no limit to the number of ways that the circuit elements can be arranged in the network.

The set of standard circuit elements does not include electronic components, but in many cases, these components are easily simulated by means of equivalent circuits constructed of standard elements. A number of examples are included in the user's manual that involve the use of equivalent circuits.

ECAP can handle electrical networks that contain as many as 50 nodes (not including ground nodes) and 200 branches.

ECAP is very simple to use. The engineer needs no knowledge of the internal construction of the program, and no previous computer experience is required. It is necessary, however, that the user be acquainted with the methods of communication with ECAP. These include (a) the technique of describing a circuit to the program, (b) the specification of the type of analysis desired, and (c) the interpretation of the results.

11.10.3 I/CAP

I/CAP, a completely revised and augmented interactive, conversational version of the well known ECAP Program, was designed by engineers, for engineers, to help them solve their circuit analysis problems via a powerful time-sharing computer, and to provide them with many features not found in most other T/S circuit analysis programs.

The prime object of this general purpose, interactive Computer-Aided Design program should be to help the user solve his particular problem, in the fastest, most convenient, and cost-effective manner.

11.10.4 CSM/O/P

Continuous Systems Modeling & Optimizing Program (CSM/O/P) is an augmented and improved version of CSMP*, designed for on-line, interactive, transient and AC simulation of continuous systems and processes. The engineer or scientist uses a simple, yet versatile application-oriented input language for simulating and evaluating systems which can be expressed either by an analog block diagram, or by a set of ordinary, or nonlinear, differential equations.

A large complement of functional elements is provided, and many time-sharing features are used to advantage to achieve operational flexibility for on-line experimentation. Program features include:

- *Conversation, discipline oriented input language
- *Predictor-corrector, or central-Euler integrations
- *Expanded element block and functions capabilities
- *AC analysis, frequency and phase response plots
- *Graphical output, and selective output control
- *On-line file handling and editing capability
- *Response optimization of linearized systems by parameter iteration under program control
- *Printout of the 'A' matrix, and eigenvalues

The user describes his problem by entering block parameter and inter-connection data, simulating a standard analog computer 'patch-board' connections and gain settings. 75 blocks, and 43 different block types are available, with provisions for additional user defined blocks. Moreover, each block has extended capabilities of operation, so that systems which would require more than 125 blocks with other programs, can easily be handled with CSM/O/P. Realistic system simulations can be obtained by including blocks which simulate: noise, backlash, flip-flops, etc. One to twenty transient response plots can be stored on disc files, and retrieved for later use.

Furthermore, the AC response, the 'A' matrix, and the eigenvalues, can be obtained for linear, or 'linearized' systems. Thus, the operation of mechanical, electrical, and hydraulic systems, can be fully simulated and analyzed by this program.

*CSMP - Continuous System Modeling Program

Frequency response optimization of a linearized system can be achieved. CSM/O/P allows the user to change the values of his system's parameters, under program control, so as to realize a response closer to the desired response specified. This optimization is accomplished by varying only the user-selected parameters, so as to maximize a merit function. A spiral, least-squares algorithm is used to minimize the difference between the desired frequency response, and the system's response, over a specified frequency interval.

11.10.5 FORTRAN IV and BASIC

These two programs are available for the user with programming experience. A number of library programs are available for solving many intricate mathematical and scientific problems.

11.10.6 Analog Computer

An analog computer COMCOR Ci-5000 is available for analog simulation of electronic circuits or functional system blocks. The COMCOR Ci-5000 is a large-scale all solid-state general-purpose computing system which consists of an analog section, a digital control section and a patchable logic section. The operating flexibility of the system permits accurate, reliable, and efficient operation with a choice of many configurations and peripheral input/output devices.

11.10.7 SUMT

The computer program implementing the Sequential Unconstrained Minimization Technique solves nonlinear simultaneous equations to determine either a minimum or maximum value. This is a research tool developed by Research Analysis Corporation, McLean Virginia, implementing many of the computational techniques for solving nonlinear programming problems set forth in Chapter 8 of the book, "Nonlinear Programming: Sequential Unconstrained Minimization Techniques," by Fiacco and McCormick. The mixed interior-exterior penalty function is used and any of several algorithms can be specified for minimizing the penalty function to accelerate the calculation procedure.

The program is modular in structure to facilitate changes in logic, options, problems and input-output. All of the subroutines are written in FORTRAN IV language, with minor modifications the program can be run on any sufficiently large computer with a FORTRAN compiler.

11.11 A DETAILED POWER PROCESSING EQUIPMENT REQUIREMENT LIST

An optimum power processor equipment design depends on the correct identification of all detailed specification requirements. These requirements generate design interactions between the internal power processor functions and determine design constraints for each function. With the advent of extremely high power equipment for future power processing systems, realistic specification requirements are vital in achieving minimum design penalties and maximum equipment compatibility.

Table 14 lists the detailed power processing equipment specifications. Each specification provides design constraints on the power processing equipment and its internal functions.

Based on these specifications, the power processing equipment designer can proceed to design the equipment to meet the correct interfaces between power source, power processor and load equipment.

TABLE 14

REQUIREMENT LIST

1. Input Source Voltage
 - a. Static - min/max value
 - b. Transient - volt-time profile
 - c. Cyclic - magnitude and frequency range
 - d. Impedance - magnitude vs. frequency
2. Output Current Demanded by Load
 - a. Static-min/max value
 - b. Transient - ampere vs. time profile
 - c. Cyclic - magnitude and frequency range
3. Impedance Characteristic of the Load
 - a. Resistive, inductive, and capacitive
 - b. Positive impedance, and negative impedance such as TWT
4. Output Power Quality of Converter
 - a. Output voltage and current rating
 - b. Power and control circuit input-output isolation
 - c. Regulation - line, load and temperature
 - d. Ripple - due to load, internal noise, and input voltage variation
 - e. Transient response due to step change in input line voltage or output load current
 - f. Output impedance - magnitude vs. frequency
 - g. Number of outputs
 - h. Efficiency

5. Protection - Control

- a. Load short circuit
- b. Output filter capacitor discharge energy control
- c. Sequencing of outputs
- d. Input, over and under voltage protection
- e. Output, over and under voltage protection
- f. ON-OFF control
- g. Special commands, ground or automatic
- h. Starting transient (input current vs. time)
- i. Internal voltage and current monitors for performance monitoring

6. Electromagnetic Interference

- a. AC reflected current versus frequency
- b. AC input current versus frequency
- c. Power source impedance versus frequency
- d. Transient input voltage during startup and fault operation
- e. Transient reflected current during startup and fault operation

7. Mechanical

- a. Weight
- b. Size of baseplate
- c. Volume
- d. Vibration - shock
- e. Location of connectors

8. Thermal

- a. Ambient temperature range
- b. Methods of heat transfer
 - Natural convection
 - Forced air
 - Radiation
 - Conduction into spacecraft structure
 - Active cooling loop

9. Reliability

- a. Mean time between failures
- b. Component peak current, voltage or power stress during steady-state, startup and fault operation
- c. Part derating
- d. Maximum component temperature
- e. Method of redundancy
 - Parallel operation
 - Standby operation
 - Quad power components
 - Majority voting
- f. Methods of fault clearing
- g. Single point failures
- h. Mission life
- i. Duty cycles

11.12 DETAILED DEFINITION OF CLASSIFICATION OF POWER PROCESSING FUNCTIONS

Each power processing equipment is constructed of a limited number of basic functional building blocks. These blocks can be grouped into power level functions and signal level functions. It is expected that a large portion of the future study will be spent on power level functions where significant system improvements can be obtained in weight and losses through the use of optimization techniques. The signal level functions, usually common to all classes of power processing equipment, are studied for their effect on the power level functions and the power processor reliability and performances.

Table 15 lists the basic power and signal functions used in power processing equipment.

Table 16 lists the basic definition for the power functions used in the power processing equipment.

Table 17 lists the different classifications for each basic power function. Mathematical models have been generated to determine actual waveforms and interaction between components in each design.

Table 18 lists the definition for the signal functions.

TABLE 15. POWER PROCESSOR CIRCUIT FUNCTIONS

POWER	SIGNAL
<u>Basic</u> Power Modulation (7 classes) Inversion (5 classes) Transformation Rectification (3 classes) Passive Filtering (11 classes) RFI Filtering Transmission <ul style="list-style-type: none"> a. Static b. Rotary Power Control & Fault Isolation	<u>Basic</u> Sensor <ul style="list-style-type: none"> a. Voltage b. Current c. Frequency References <ul style="list-style-type: none"> a. Voltage b. Current c. Frequency Analog Signal Processor <ul style="list-style-type: none"> a. Voltage Gain b. Current Gain Digital Signal Processor Power Switch Interface Driver Input/Output Ground Isolator Digital Logic Function <ul style="list-style-type: none"> a. OR Gate b. AND Gate c. Flip-flop d. Multivibrator e. Schmitt Trigger f. Counters Relay Driver Time Delay Telemetry <ul style="list-style-type: none"> a. Voltage b. Current

TABLE 16. POWER FUNCTION DEFINITIONS

1. Power Modulation

- a. Switching: The process of controlling power from a source such that the output is maintained within desired limits. The control is accomplished by varying the ON/OFF time ratio of a power switch either by a pulsewidth modulation (PWM) or by pulse rate modulation (PRM). Either process, herein, is referred to as pulse modulation (PM).
- b. Dissipative: The process of controlling power from a source such that the output is maintained within desired limits. The control involves dissipation of excess energy.

2. Inversion

The process of converting dc voltage to ac voltage or dc current to ac current.

3. Transformation

The process of converting ac voltage from one level to another, either step-up or step-down, and working as an isolation transformer or as an auto-transformer.

4. Rectification

The process of converting ac voltage to an unfiltered dc voltage.

5. Passive and RFI Filtering

The process of suppressing or minimizing frequency components in power lines with passive components. The two types considered in this study are the dc filter (those used in either dc power lines, input or output) and the ac type (used primarily for harmonic filtering in ac output power lines).

6. Transmission

The transmission of power from the power generation subsystem to other subsystems as a function of spacecraft configuration.

7. Power Control and Fault Protection

The process of distribution and switching of power, including failure detection, isolation, current limiting, and voltage limiting.

TABLE 17. POWER FUNCTION CLASSES

Power Modulation

1. Switching
 - a. PWM - Inversion
 - b. PWM - Rectification
 - c. PM - Buck
 - d. PM - Boost
 - e. PM - Buck-Boost
2. Dissipative
 - a. Series
 - b. Shunt

Inversion

1. Squarewave
 - a. Resistive Load
 - b. Rectifier-LC Filter Load
 - c. Rectifier-C Filter Load
2. Squarewave with Fixed Dwell
3. Sinewave

Rectification

1. Squarewave
2. PWM - Squarewave
3. Sinewave

Passive Filtering

1. DC Filters
 - a. LC - No ac requirement
 - b. LC - High ac current
 - c. LC - High ac voltage
 - d. LC - High ac voltage and current
 - e. LC - high ac voltage with transformation
 - f. LC - high ac voltage & current with transformation
 - g. C - No ac requirement
 - h. C - High ac current - low frequency
 - i. C - High ac current - high frequency
2. AC Filters
 - a. LC - High ac voltage and current
 - b. C - High ac current

TABLE 18. SIGNAL FUNCTION DEFINITIONS

1. Sensor

The sensor monitors the output parameters including voltage, current or frequency, and converts the signal so that it is compatible with the remainder of the control electronics.

2. Reference

In all feedback control systems, a reference or standard must be provided which has its own required accuracy to maintain the power conditioner within its specification requirements.

3. Analog Signal Processor

An active network for obtaining a controlled voltage (or current) gain versus frequency characteristic.

4. Digital Signal Processor

This is the brain of all switching regulating systems, which controls the ON/OFF of the power switch. Basically, it is an active network for converting variable analog signal levels to a digital signal having either variable pulse width or variable pulse frequency to drive the switching power transistor.

5. Power Switch Interface Driver

The power switch in most high power applications requires interface circuitry to provide the correct current level, voltage level shift and impedance matching between the digital signal processor and the power switch.

6. Input/Output Ground Isolation

In most power conditioning there is a need for input/output ground isolation. This device passes a digital type signal from the output sensing to the main power switch controller to achieve the control-circuit input/output isolation. This is in addition to the power-circuit isolation, which is achieved by the proper choice of power modulation and inversion scheme.

7. Digital Logic Functions

These are standard functions used in processing digital signals to provide the correct operation of the power conditioning equipment.

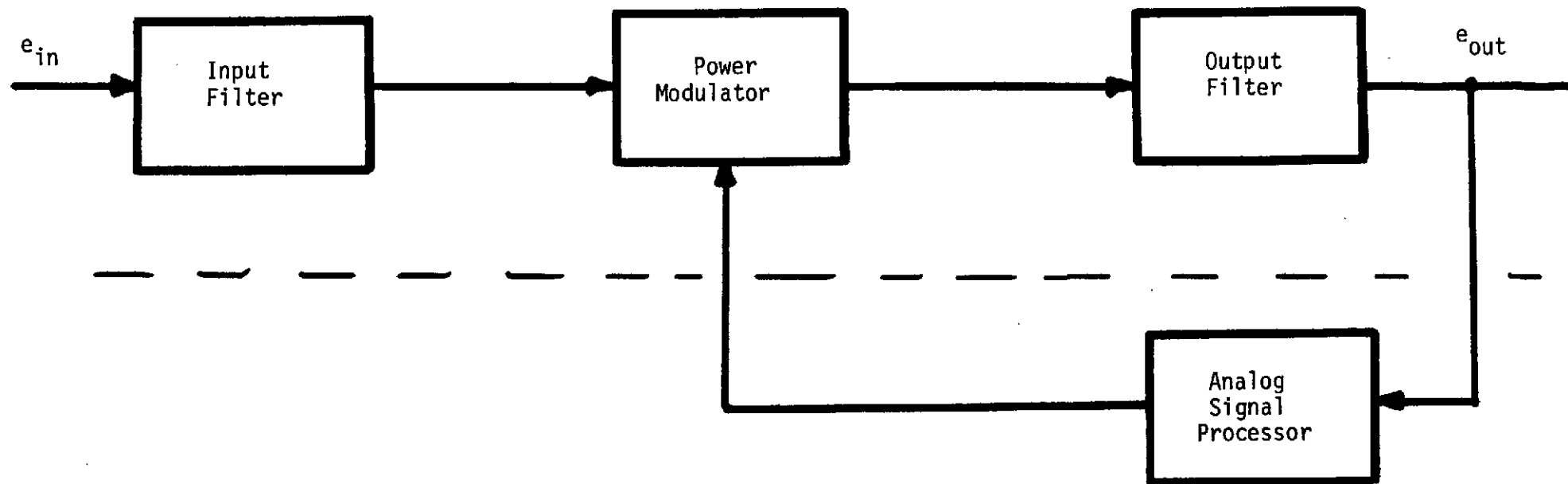
11.13 POWER PROCESSING EQUIPMENT FUNCTIONAL BLOCK DIAGRAMS

Figures 22 through 27 illustrate the power processing equipment used in dc power distribution systems, based on the standard power processing equipment functions.

Figures 28 through 30 illustrate the power processing equipment used in ac power distribution systems.

Figure 31 illustrates the block diagram for the source/load power distribution unit.

POWER FUNCTIONS

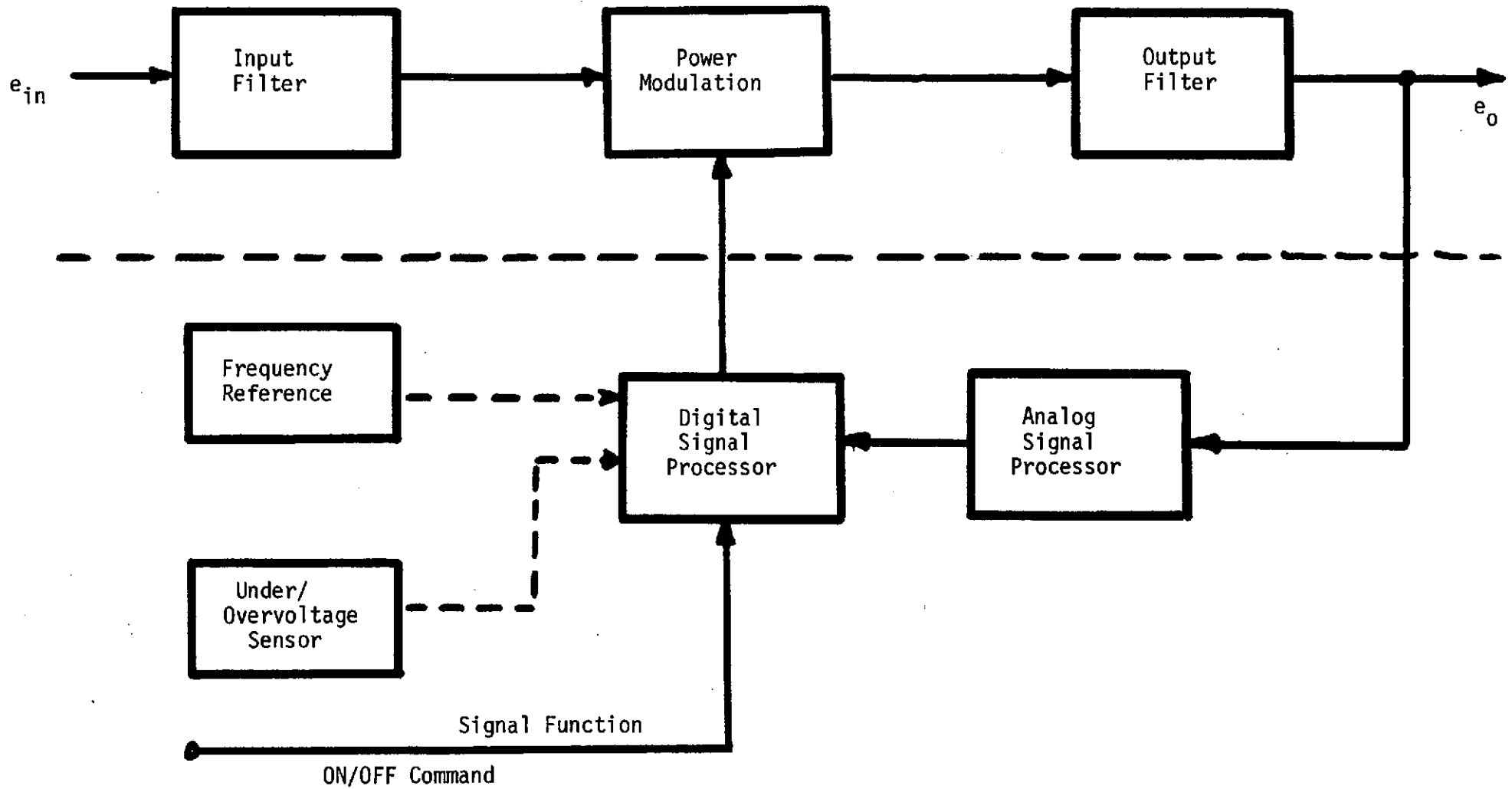


SIGNAL FUNCTIONS

DC LINE REGULATOR (DISSIPATIVE) FUNCTIONAL BLOCK DIAGRAM

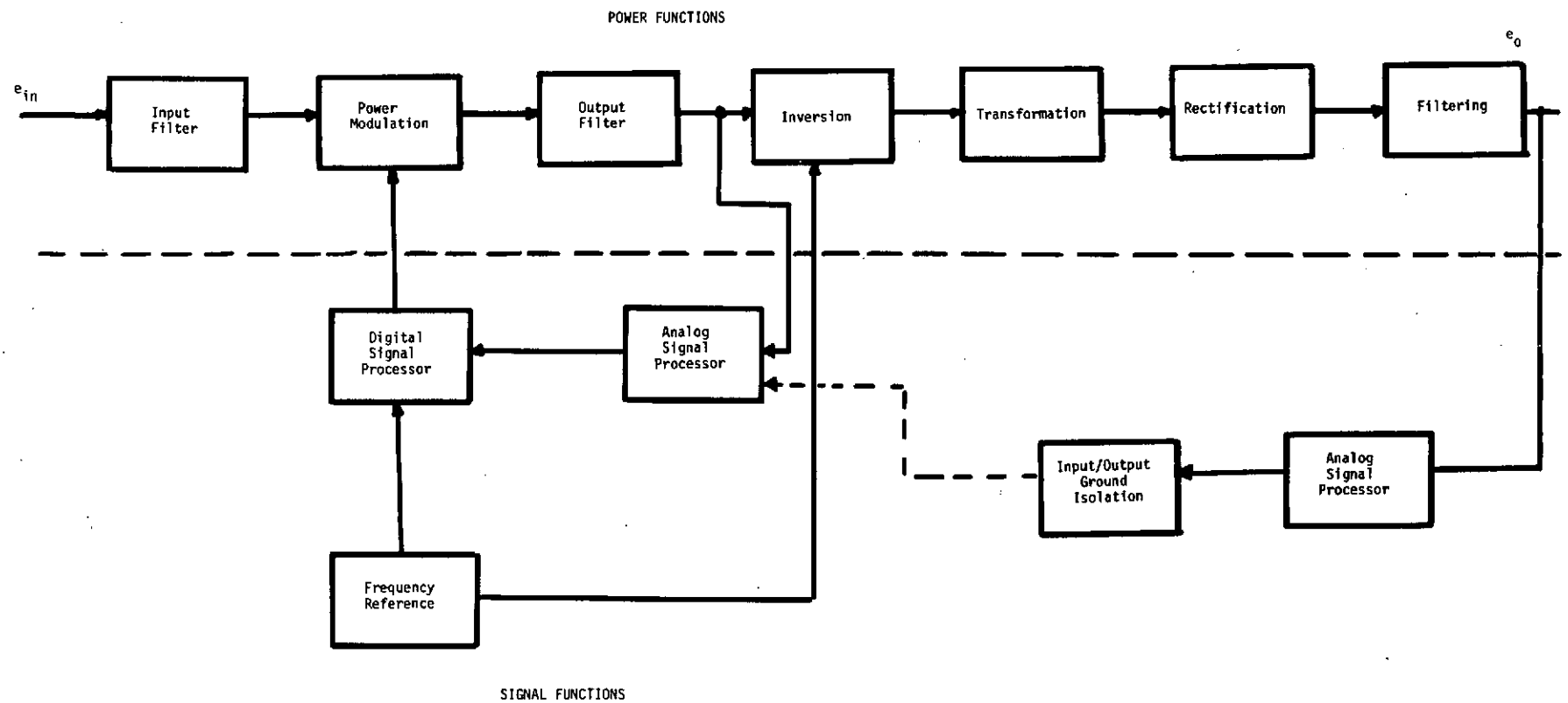
Figure 22

POWER FUNCTION



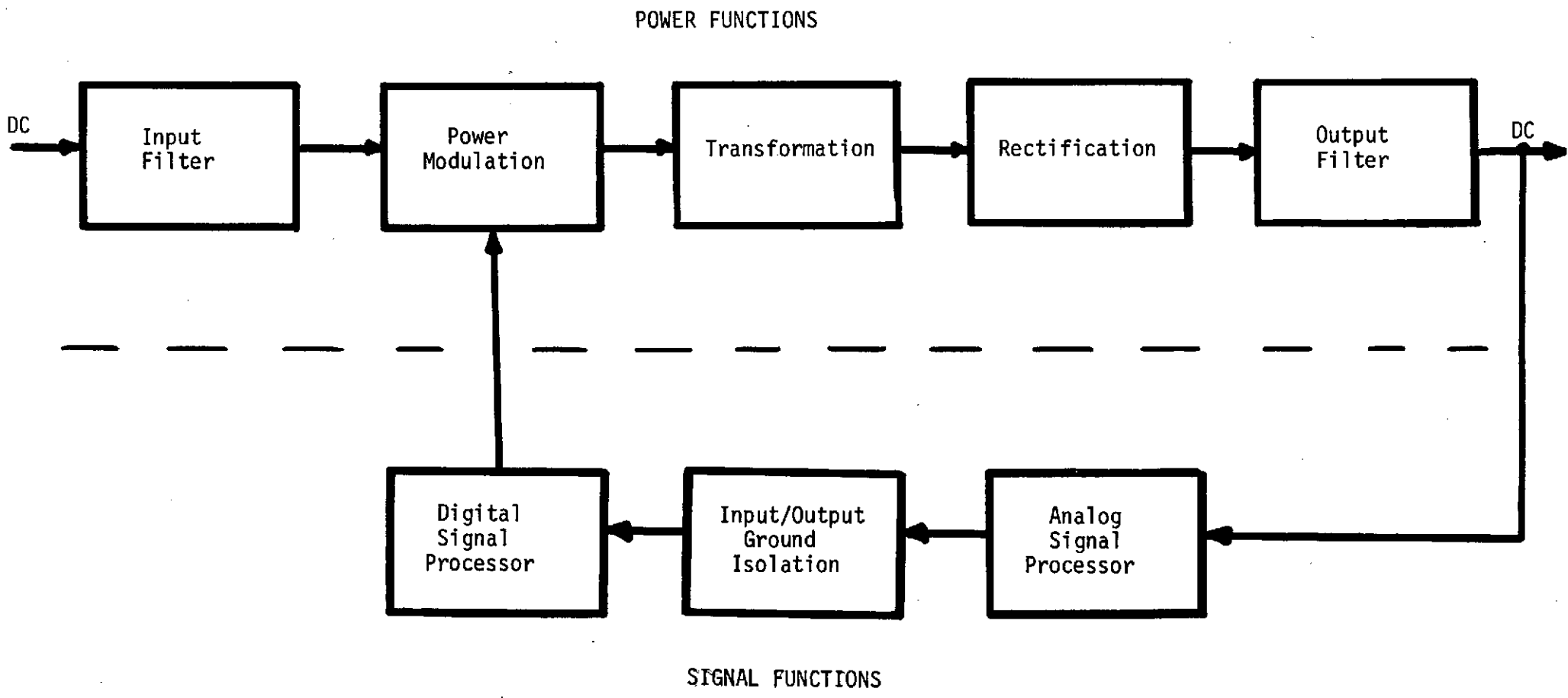
DC LINE REGULATOR (SWITCHING) FUNCTIONAL BLOCK DIAGRAM

Figure 26



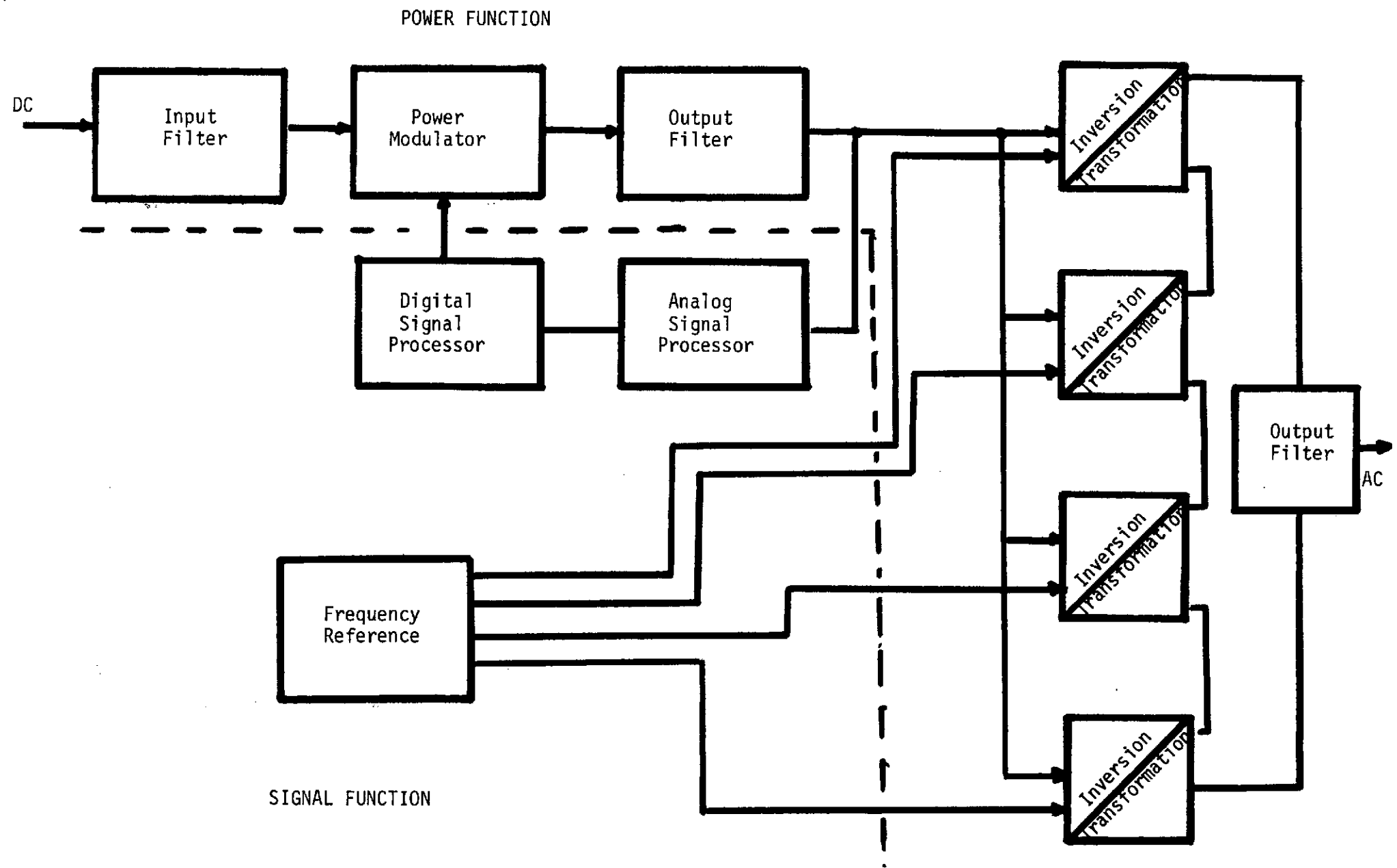
DC-DC CONVERTER (PREREGULATOR/SQUAREWAVE INVERTER)

Figure 24



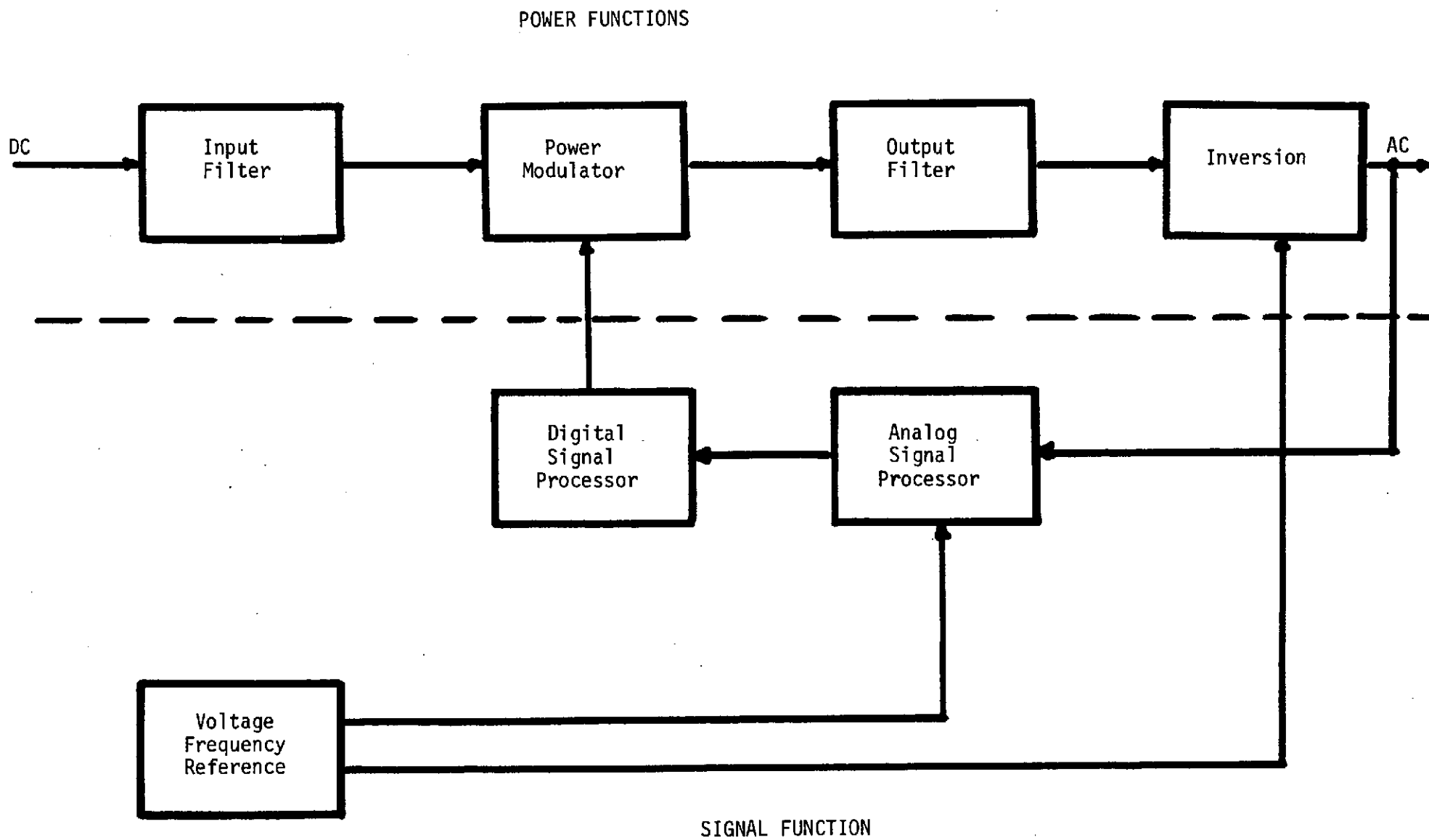
DC-DC CONVERTER (PULSEWIDTH MODULATED INVERTER)

Figure 25



DC TO AC INVERTER (STEP WAVE FORM) FUNCTIONAL BLOCK DIAGRAM

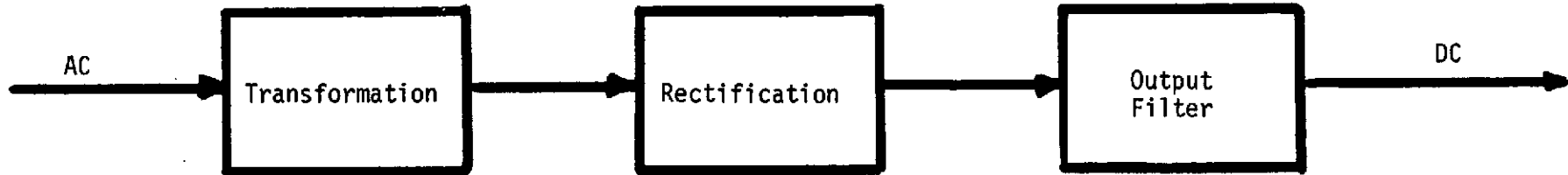
Figure 26



DC TO AC INVERTER (HIGH FREQUENCY PULSEWIDTH MODULATION) FUNCTIONAL BLOCK DIAGRAM

Figure 27

POWER FUNCTIONS

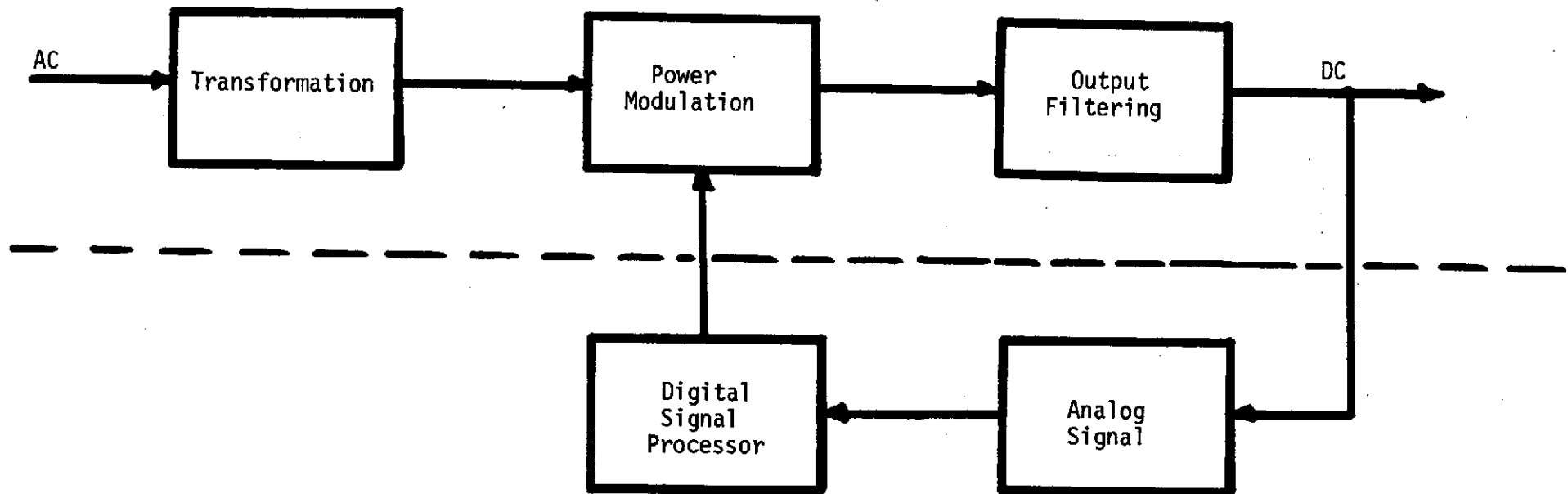


NO SIGNAL FUNCTIONS

AC-DC CONVERTER (UNREGULATED)

Figure 28

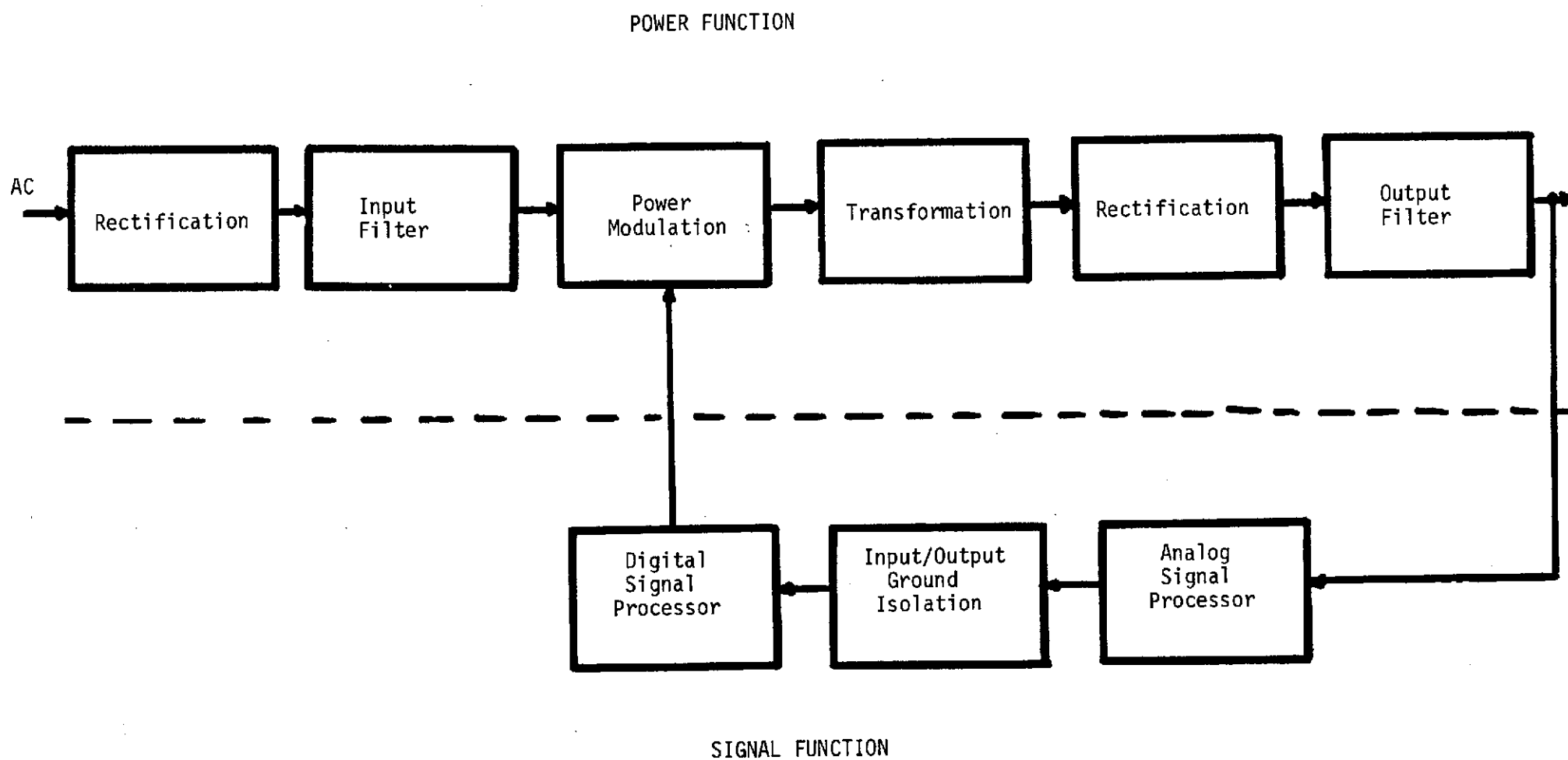
POWER FUNCTIONS



SIGNAL FUNCTIONS

AC-DC CONVERTER (REGULATED) (LOW FREQUENCY OPERATION)

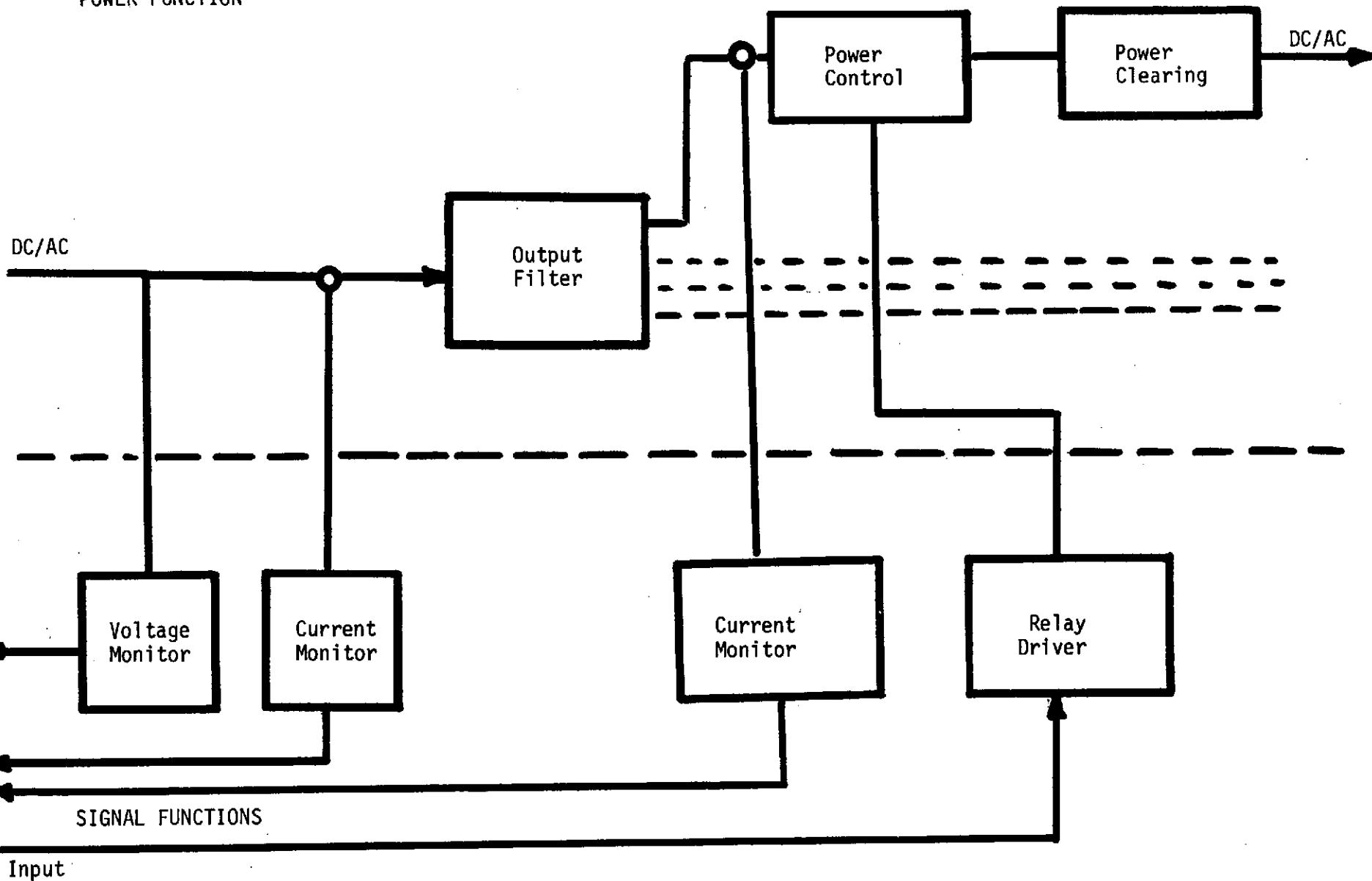
Figure 29



AC-DC CONVERTER (HIGH FREQUENCY OPERATION) - REGULATED

Figure 30

POWER FUNCTION



SOURCE/LOAD POWER DISTRIBUTION UNIT
Figure 31

11.14 A NUMERICAL EXAMPLE ON THE INTERDEPENDENCE AMONG POWER PROCESSING FUNCTIONS

In conducting the PPE tradeoff study, the designer becomes keenly aware of the interdependence existing among the PPE functional blocks. Invariably, he found that the impact of selecting a design approach for the implementation of a given functional block is frequently felt by all other PPE functional blocks. Unfortunately, there is a dearth of design information leading to an effective assessment of the interdependence. As a result, the full impact of the interdependence can be made apparent only after the completion of rather laborious quantitative studies. Pressed by schedule and cost, this interdependence is often overlooked or hastily defined, thus incurring PPE weight and loss penalties.

To illustrate this interdependence, the basic power circuit of a buck-boost switching regulator is shown in Figure 32. Design variations for the "power modulation and transformation" block will be shown to impact directly on the input and output passive filtering blocks, thereby extending its influence to the overall PPE.

Depending on the load variation, the MMF in the inductor transformer T in Figure 32 can be designed to exhibit one of the following three patterns: (1) the MMF is never zero, i.e., the inductor is designed to be high above critical inductance for all loads, (2) A dwell at zero MMF always exists during a portion of the power-switch off time, i.e., the inductor is designed to be below critical inductance for all loads, and (3) the non-zero MMF of case (1) exists at heavy load, and a zero MMF of case (2) at lighter loads, i.e., the critical inductance occurs at an intermediate load.

What design should be selected depends on detailed tradeoffs involving the combined efficiency and weight of the input filter, the power transformer, the semiconductors, and the output filter. The first alternative above would yield maximum inductor weight and copper losses, but would produce less weights in the input/output filters and less core loss in the inductor transformer. The second alternative is the opposite, while the third alternative provides an intermediate compromise. A detailed design calculation was performed using each of the three designs described. The designs are based on identical input/output requirements specified below. To meet all these requirements, the design data for the circuit of Figure 3.5 are summarized in Table 19.

Input Voltage: 20V to 40V
 Output Voltage: 28V regulated
 Output Power: 40 watts
 Frequency: 25kHz
 Output Ripple: One percent peak-to-peak
 Source Current: Meet MIL-STD-461A, Notice 3

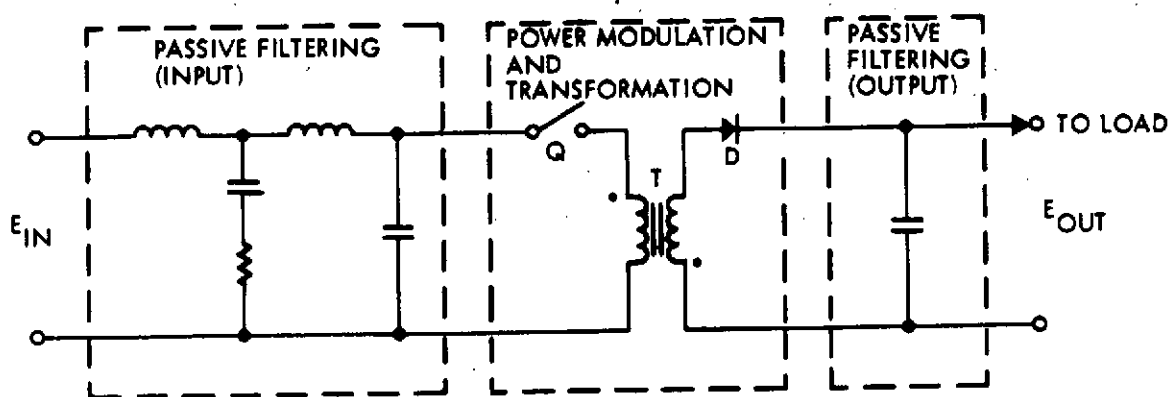


Figure 32 Buck-Boost Switching Regulator

TABLE 19

Weight and Loss Analysis Demonstrating the Interdependence of Functional Blocks

	Input Filter			Power Modulation & Transformation			Output Filter			Total		
	Design No. 1	Design No. 2	Design No. 3	Design No. 1	Design No. 2	Design No. 3	Design No. 1	Design No. 2	Design No. 3	Design No. 1	Design No. 2	Design No. 3
Component Weight (Grams)	82	108	82	275	85	125	40	80	40	397	277	243
Power Loss (Watts)	0.30	0.31	0.30	4.07	3.50	3.15	0.1	0.1	0.1	4.47	3.91	3.55

↓
 Minimum
Weight
and
Loss

This example thus adequately demonstrates the functional interdependence. By designing the "Power Modulation and Transformation" block with all three different approaches, the impact of each design on all functional blocks is quantitatively revealed. The optimum PPE design is thus identified to be Design No. 3, which yields minimum weight and minimum losses.

The analysis and modeling techniques to be developed in this program can be most effective and meaningful only if they provide a means of achieving the illustrated optimization among all interdependent functions. This is considered essential in developing useful design, analysis, and modeling techniques, without which the utility of the techniques developed would be extended only to optimization at the functional level, and would have no validity in arriving at an optimum PPE design.

Another functional block interdependence of different nature concerns the overall PPE integration. Most of switching-regulated PPE are essentially negative-impedance devices, which can contribute to the formation of a low-frequency limit cycle when it is integrated into a low damping, second-order energy storage device.

The paper presented in Reference [36] uses an input filter to represent this energy-storage device. Conditions of a stable limit cycle are derived using the method of singularity, and the analytical results have been experimentally substantiated.

11.15 AN EXAMPLE OF CLOSED-FORM OPTIMUM-WEIGHT MAGNETICS DESIGN EQUATION

Introduction

The design of a toroid inductor is normally achieved rather routinely. Based on information concerning the inductance L needed, the peak current I_p through it, and the saturation flux density B_s of the core material, the designer starts with a core having area A , mean length z , window area A_w , and permeability μ . The number of turns N needed to make inductance L is then calculated.

At this point two comparisons are made: (1) $\mu NI_p/z = \mu H_p$ is compared to B_s to see if the magnetic capability is fully utilized, and (2) N is multiplied by A_c (i.e., A_c being the sectional area of copper per each turn of conductor as required to handle the winding current with peak value I_p) to see if the window area A_w is sufficient to accommodate the windings, from which the relative value of A_w with respect to $NA_c/F_w = A_x$, where F_w is the estimated winding factor, is determined. Six possibilities would emerge from these comparisons, namely;

$$(A) \mu H_p > B_s, A_x > A_w, (B) \mu H_p > B_s, A_x < A_w, (C) \mu H_p < B_s, A_x > A_w,$$

$$(D) \mu H_p < B_s, A_x \approx A_w, (E) \mu H_p \approx B_s, A_x > A_w, \text{ and } (F) H_p \approx B_s, \text{ and } A_x \approx A_w.$$

Cases (A), (B), and (C) point to either core saturation or inability to accommodate all windings within the given window area, indicating the need for a larger core. Case (D) represents a surplus in the magnetic capability of the core; a higher μ and smaller core may be in order. As for case (E), the fact that the window is left unfilled is synonymous to the need for a lower μ and smaller core for space utilization. Only case (F) represents an inductor design utilizing fully the electromagnetic capability provided by the core-winding combination.

It is highly unlikely, even for an experienced designer, to choose the right core so that case (F) is achieved in the first try. More often than not, many passes will be taken before case (F) can be arrived at. Furthermore, there normally exists a number of designs, all of which can satisfy conditions specified in case (F). However, only one of them would provide the lightest combined core and wire copper weight. The minimum inductor weight equations will result in different inductor designs for different conductor sizes selected.

The objective of this discussion is to determine, for a given L , B_s , and A_c , what particular set of A , N , z , and μ will give the combination of least iron and copper weight.

Nomenclatures and Assumptions

The following symbols are used in this section.

- A: Core sectional area in meter²
- A_c : Copper-conductor area per turn in meter²
- A_w : Window area of toroid core in meter²
- B_s : Saturation flux density of the core material in weber/m²
- D_c : Specific gravity of the copper conductor in kg/m³
- D_i : Specific gravity of the magnetic core in kg/m³
- F_w : Winding factor
- F_c : The ratio of mean length per turn of copper conductor to the circumference of the core section, i.e., the pitch factor
- I_p : Peak current in ampere in the inductor winding
- L: Inductance in Henry's
- N: Number of turns
- μ : Permeability of the core material in MKS unit, and
- z: Mean length of the circular magnetic path in meters.

While the method presented herein is applicable to any core section configuration, a square toroid core section is assumed for convenience. Thus, for a core cross-sectional area A , the circumference of the core section is $4\sqrt{A}$. The mean length per turn of copper conductor is, therefore, $4F_c\sqrt{A}$.

Problem Formulation

Using the aforementioned symbols, two basic equations can be written as:

$$\frac{\mu N^2 A}{z} = L \quad (1)$$

and

$$\frac{\mu N I_p}{z} = B_s \quad (2)$$

Combining these two equations gives:

$$NA - \frac{L I_p}{B_s} = 0 \quad (3)$$

The window area is

$$A_w = \pi r^2 = \pi \left(\frac{z}{2\pi} - \frac{\sqrt{A}}{2} \right)^2$$

where r is the inside radius of the core. Multiplying A_w by the winding factor, F_w , gives the total copper area. Assuming that the window is filled, then $NA_c/F_w = A_w$ gives

$$\frac{NA_c}{\pi F_w} = \left(\frac{z}{2\pi} - \frac{\sqrt{A}}{2} \right)^2$$

or

$$\sqrt{\frac{A_c}{\pi F_w}} \cdot \sqrt{N} - \frac{z}{2\pi} + \frac{\sqrt{A}}{2} = 0 \quad (4)$$

As noted before, the mean length per turn of the copper conductor is $4F_c\sqrt{A}$. The total copper and iron weight, W_t , is, thus;

$$W_t = 4F_c A_c D_c N \sqrt{A} + D_i A_z \quad (5)$$

The mathematical problem of minimizing inductor weight is now defined as the following: Find the values for A, N, and z to cause a minimum W_t in equation (5) using equations (3) and (4) as constraints. Also find μ from equation (2) for this particular set of A, N, and z.

Analytical Solutions Using LaGrange Multipliers

A necessary condition for $f(x, y, z)$ to have a minimum when x, y, z , are subjected to the constraints of

$$P(x, y, z) = 0 \quad \text{and} \quad q(x, y, z) = 0$$

may be found by adding to these two equations the conditions that the function:

$$h(x, y, z) = f(x, y, z) - \alpha P(x, y, z) - \beta q(x, y, z)$$

has a minimum, where α and β are as LaGrange Multipliers. Specifically, in addition to $p(x, y, z) = 0$ and $q(x, y, z) = 0$, one has the following three more equations:

$$\frac{\partial h}{\partial x} = 0, \quad \frac{\partial h}{\partial y} = 0, \quad \frac{\partial h}{\partial z} = 0$$

These five equations can be used to solve the five unknowns x, y, z, α and β .

Relating the foregoing discussion to the present problem, $f(x, y, z)$ corresponds to eq. (5), $p(x, y, z)$ and $q(x, y, z)$ are equivalent to eqs. (3) and (4), thus;

$$\begin{aligned} f(x, y, z) &= 4F_c D_c A_c xy^2 + D_1 x^2 z, \quad y = \sqrt{N}, \quad x = \sqrt{A} \\ P(x, y, z) &= x^2 y^2 - \frac{LI}{B_s} p = 0 \end{aligned} \quad (6)$$

$$q(x, y, z) = \sqrt{A_c} \sqrt{\pi F_w} \cdot y - \frac{z}{2\pi} + \frac{x}{2} = 0 \quad (7)$$

Therefore,

$$h(x, y, z) = 4F_c D_c A_c xy^2 + D_1 x^2 z - \alpha \left(x^2 y^2 - \frac{LI}{B_s} p \right) - \beta \left(\sqrt{\frac{A_c}{\pi F_w}} y - \frac{z}{2\pi} + \frac{x}{2} \right)$$

$$\frac{\alpha h}{\alpha x} = 4F_c A_c D_c y^2 + 2D_i zx - 2\alpha xy^2 - \frac{\beta}{2} = 0 \quad (8)$$

$$\frac{\alpha h}{\alpha y} = 8F_c A_c D_c xy - 2\alpha x^2 y - \beta \sqrt{\frac{A_c}{\pi F_w}} = 0 \quad (9)$$

$$\frac{\alpha h}{\alpha z} = D_i x^2 + \frac{\beta}{2\pi} = 0 \quad (10)$$

Solving eqs. (6) to (10) for the non-trivial solutions, one obtains:

$$A = \frac{1}{3} \left(\frac{LI_p A_c}{B_s \pi F_w} \right)^{1/2} S \quad (11)$$

$$N = 3 \left(\frac{LI_p A_c}{A_c B_s} \right)^{1/2} S^{-1} \quad (12)$$

$$z = 2 \sqrt{3} \pi \left(\frac{LI_p A_c}{B_s \pi F_w} \right)^{1/4} (S^{-1/2} + \frac{S^{1/2}}{6}) \quad (13)$$

$$\mu = \frac{2\pi}{\sqrt{3}} \left(\frac{B_s}{I_p} \right)^{5/4} \left(\frac{A_c}{\pi F_w} \right)^{3/4} L^{-1/4} S (S^{-1/2} + \frac{S^{1/2}}{6}) \quad (14)$$

$$S = \left(1 + \frac{12F_c F_w D_c}{D_i} \right)^{1/2} - 1$$

Equations (11) to (14) illustrate the particular set of A, N, z, and μ that will produce the minimum combined copper and iron weight for an inductor with inductance L, peak winding current I_p , winding cross-sectional area A_c , saturation flux density B_s , winding factor F_w , pitch factor F_c , specific gravities D_c for copper and D_i for the core. Here, A and z are in meters, and μ in Weber/Amp-turn-meter. To convert μ into Gauss/oersted, eq. (14) would have to be divided by $4\pi \times 10^{-7}$.

As one would expect from a problem of this complex nature, the equations obtained are not as simple as we like them to be. However, they are certainly not incompatible with actual slide-rule evaluations. Furthermore, the equations are readily adaptable for computer processing. In reality, of course, it is rather unlikely that a commercially available core would exist to match precisely those characteristics defined in eqs. (11) to (14), and that the

mismatch would probably be most prominent for permeability μ , where a few discrete ones can be chosen commercially. Nevertheless, these equations do provide a guideline in designing an optimum weight inductor. The selective process is accomplished without time-consuming iterations, yet it results in the minimum combined iron and copper weight for the required inductor.

Minimum Inductor Weight

Using equations (5), (11), (12), and (13), the minimum W_t in kilograms can be shown to be

$$(W_t)_{\text{Min}} = \frac{2\pi D_c}{\sqrt{3}} \left(\frac{LI_p A_c}{B_s \pi F_w} \right)^{3/4} S^{-1/2} \left[6F_c F_w + \frac{D_i}{D_c} \left(S + \frac{S^2}{6} \right) \right] \quad (15)$$

11.16 AN EXAMPLE OF DERIVING DESIGN EQUATIONS FOR A POWER PROCESSING FUNCTION

The filter schematic is shown in Figure 33. The design procedures starts with the derivation of its transfer function:

$$G(s) = \frac{I_1(s)}{I_0(s)} = \frac{1 + SC_1 R_1}{\left[\frac{C_2}{C_1} (1 + SC_1 R_1) + (1 + S^2 L_2 C_2) \right] (1 + SC_1 R_1 + S^2 L_1 C_1) - \left(\frac{C_2}{C_1} \right) (1 + SC_1 R_1)} \quad (1)$$

Three frequencies of particular interest are: (1) the first-stage filter resonant frequency f_1 , (2) the second-stage resonant frequency f_2 , and (3) the switching frequency F of the converter.

(1) At f_1 where $S^2 L_1 C_1 = -1$, the peaking P_1 can be derived from eq. (1):

$$P_1 = \left| G(j2\pi f_1) \right| = \left\{ \frac{1 + D^2}{\left(\frac{C_2}{C_1} \right)^2 + D^2 \left[1 - \frac{C_2}{C_1} - \left(\frac{f_1}{f_2} \right)^2 \right]^2} \right\}^{\frac{1}{2}} \quad (2)$$

Here, D is the damping factor of the first stage, i.e.,

$$R_1 = D \sqrt{\frac{L_1}{C_1}} \quad (3)$$

(2) At f_2 where $S^2 L_2 C_2 = -1$, the peaking P_2 can be derived from eq. (1):

$$P_2 = \left| G(j2\pi f_2) \right| = L_2 / L_1 \quad (4)$$

The resonance of the low-damping second-stage is thus effectively clamped to a value corresponding to L_2/L_1 by the presence of the first stage. Since $L_2 < L_1$ is normally observed, peaking of P_2 beyond 0-db is impossible.

(3) At F where $F \gg f_1$ and $F \gg f_2$, it can be shown from eq. (1) that the attenuation $G(s) = A \ll 1$ becomes

$$A = \left| G(j2\pi F) \right| = \frac{1}{\left(\frac{f_1}{f_2} \right)^2 \left(\frac{F}{f_1} \right)^3 \left(\frac{1}{D} \right) - \left(\frac{C_2}{C_1} \right) \left(\frac{F}{f_1} \right)^2} \quad (5)$$

Solving for approximate (F/f_1) from (5) gives

$$\frac{F}{f_1} \approx \sqrt[3]{\frac{1}{\left(\frac{f_1}{f_2}\right)^2 \left(\frac{1}{D}\right) (A)}} + \frac{D \left(\frac{L_1}{L_2}\right)}{3} \quad (6)$$

Based on these design criteria and the transfer functions, a design procedure can be outlined as the following

- (1) Calculating the maximum alternating current in C_2 based on given line and load conditions.
- (2) Based on the calculated current, choose suitable capacitors for C_2 so that the maximum steady-state ripple voltage across C_2 is within the allowance of the design criteria.
- (3) Choose the proper ratio for C_2/C_1 and L_2/L_1 . As stated earlier, the ratio L_2/L_1 should be less than unity to avoid the second-stage peaking beyond 0-db. (Recommended value is in the range between 1/2 to 1/4). Furthermore, in order to meet the 3db peaking requirement, $L_1 C_1$ should be at least more than four times larger than $L_2 C_2$ in order to avoid the closeness of f_2 to f_1 . (Recommended value is between three and six times).
- (4) Solving D^2 in eq. (2) gives

$$D^2 = \frac{1 - P_1^2 (C_2/C_1)^2}{P_1^2 \left[1 - (C_2/C_1) \left(1 + \frac{L_2}{L_1} \right) \right]^2 - 1} \quad (7)$$

In conjunction with the chosen C_2/C_1 and L_2/L_1 , eq. (7) can be used to calculate the damping factor D in order to limit the resonant peaking to P_1 as specified in the design criteria.

- (5) With a required attenuation A at a given switching frequency F , eq. (6) can be used to calculate f_1 .
- (6) Determine L_1 from

$$L_1 = \frac{1}{(2\pi f_1)^2 C_1}$$

- (7) Obtain L_2 from the chosen ratio L_2/L_1 .
- (8) From eq. (3) calculate R_1 .
- (9) Use the magnetics design equations presented in Appendix 11.15 to estimate the inductor weight. The capacitor weights are specified by the manufacturers. From these results, the total filter component weight is obtained.

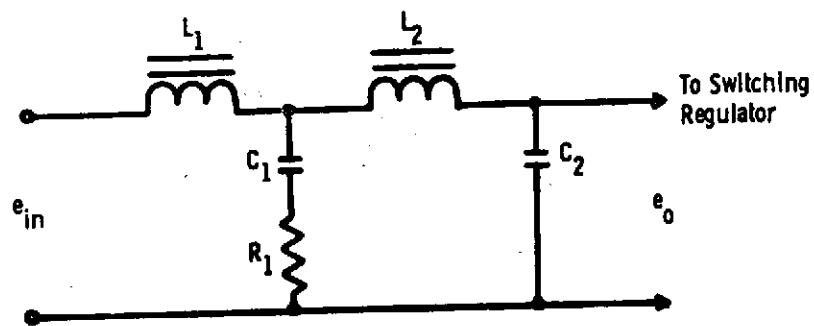


Figure 33 A Two-Stage Input Filter

11.17 AN EXAMPLE OF POWER PROCESSING COMPONENT STRESSES AS DETERMINED FROM FUNCTIONAL DESIGN EQUATION

An important aspect of input filter design is the determination of the rms current rating of the filter output capacitor. This capacitor supplies pulse current in switching regulator applications. Three commonly used regulators, with associated input filters, are illustrated in Figs. 34 (A), (B) and (C); the

buck regulator, the buck-boost regulator and the boost regulator. The rms current in the filter capacitor C is derived, in the following paragraphs, for each regulator type, showing the dependence on line voltage, load and circuit parameters.

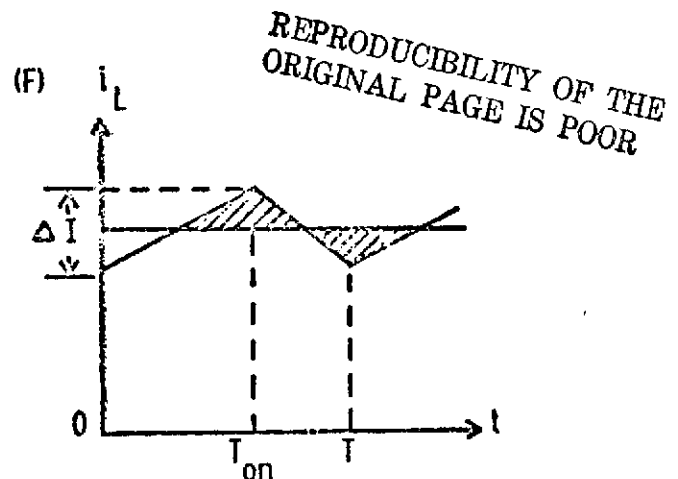
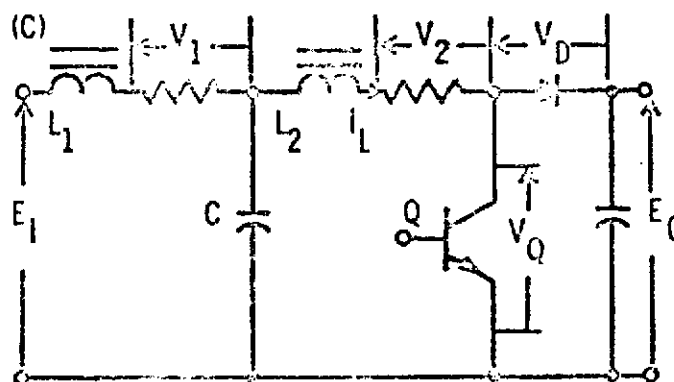
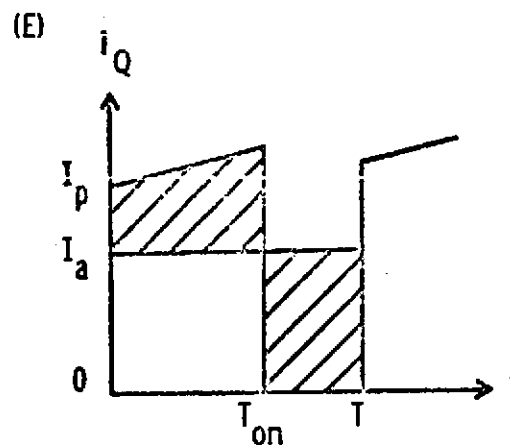
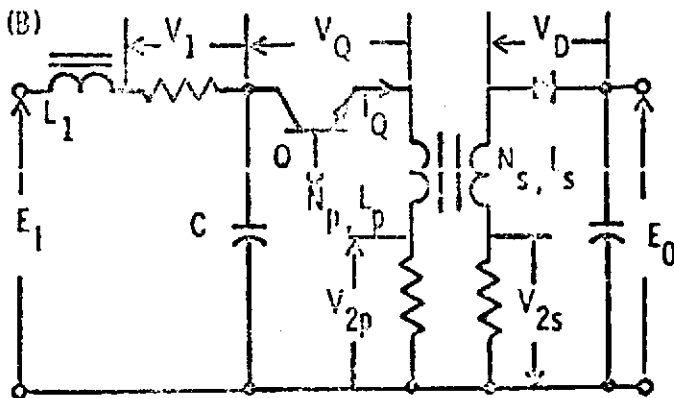
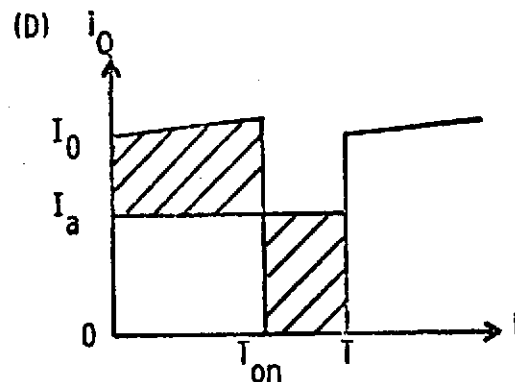
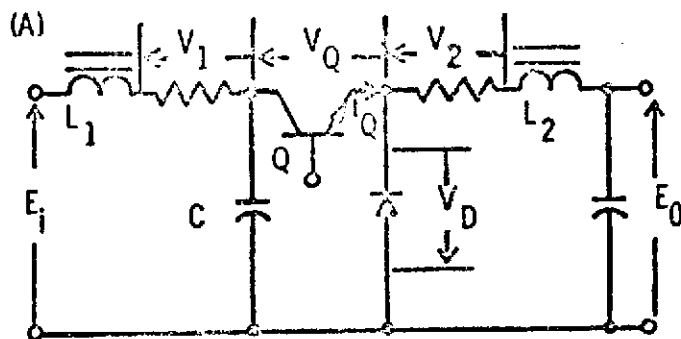


FIGURE 34 Regulator Types: (A) Buck, (B) Buck-Boost, (C) Boost
Alternation Current in Respective Input Filter Capacitor Represented by Shaded Areas: (D), (E), (F).

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Buck Regulator

From Fig. 34 (A), volt-second balance on the output inductor, L_2 , requires that:

$$(E_i - V_1 - V_Q - V_2 - E_o) T_{on} = (E_o + V_D + V_2) T_{off} \quad (1)$$

By assuming a sufficiently large value of L_2 and a large load demand, an essentially rectangular current pulse, shown in Figure 34 (D) flows through Q . The average value of this current over a full cycle is I_a . The average load current, I_o , which is also the amplitude at the center of the current pulse, can be expressed as:

$$I_o = I_a \frac{T}{T_{on}} \quad (2)$$

The alternating current through C is represented by the two shaded areas. Its rms value is

$$\begin{aligned} i_{rms} &= \sqrt{\frac{1}{T} \left[\int_0^{T_{on}} (I_o - I_a)^2 dt + \int_{T_{on}}^T I_a^2 dt \right]} \\ &= I_o \sqrt{\frac{T_{on}}{T} \left[1 - \left(\frac{T_{on}}{T} \right) \right]} \quad (3) \end{aligned}$$

The maximum rms current occurs for $\frac{T_{on}}{T} = 0.5$ and is equal to $\frac{I_o}{2}$.

Neglecting V_1 , V_Q , V_D and V_2 in Figure 2(A), $\frac{T_{on}}{T} = 0.5$ occurs when $E_i = 2E_o$. For a more accurate calculation, the substitution of (1) in (3) gives:

$$i_{rms} = \frac{I_o}{E_i - V_1 - V_Q + V_D} \sqrt{(E_o + V_2 + V_D)(E_i - V_1 - V_Q - V_2 - E_o)} \quad (4)$$

Buck-Boost Regulator

Volt-second balance on the two-winding inductor requires that:

$$N_s T_{on} (E_i - V_1 - V_Q - V_{2p}) = N_p T_{off} (E_o + V_D + V_{2s}) \quad (5)$$

As in the previous case, a sufficiently large value of L_2 and a large load demand are assumed so that a current pulse, as shown in Fig. 34 (E), flows through Q . The full-cycle average value of current, I_a , is related to the pulse amplitude, I_p , by:

$$I_p = I_a \frac{T}{T_{on}} = \frac{P_o T}{E_i T_{on}} \quad (6)$$

The alternating current through C , as represented by the shaded areas of Fig. 34 (E), is:

$$\begin{aligned} i_{rms} &= I_p \sqrt{\frac{T_{on}}{T} \left[1 - \left(\frac{T_{on}}{T} \right) \right]} \\ &= \frac{P_o}{E_i N} \sqrt{\frac{(E_i - V_1 - V_Q - V_{2p}) N_s}{(E_o + V_D + V_{2s}) N_p}} \quad (7) \end{aligned}$$

The maximum value of i_{rms} thus occurs at $E_i = 2(V_1 + V_Q + V_{2p})$. Normally, this particular value of E_i is much below the minimum input voltage. For higher E_i , within the operating range, i_{rms} decreases with increasing input voltage, E_i .

Boost Regulators

For the boost regulator shown, the alternating current component in filter capacitor C is as depicted in Fig. 34 (F), where:

$$\begin{aligned} \Delta I &= \frac{E_i - V_1 - V_2 - V_Q}{L_2} T_{on} \\ &= \frac{E_o + V_D + V_1 + V_2 - E_i}{L_2} T_{off} \quad (8) \end{aligned}$$

For systems operating with, respectively, constant T_{on} , constant $E_i T_{on}$, constant T_{off} and constant T , the corresponding i_{rms} values are given by:

$$i_{rms} = \frac{E_i - V_1 - V_2 - V_Q}{2\sqrt{3} L_2} T_{on} \quad (9)$$

$$i_{rms} = \frac{1 - [(V_1 + V_2 + V_Q)/E_i]}{2\sqrt{3} L_2} E_i T_{on} \quad (10)$$

$$i_{rms} = \frac{E_o + V_D + V_1 + V_2 - E_i}{2\sqrt{3} L_2} T_{off} \quad (11)$$

$$i_{rms} = \frac{E_i - V_1 - V_2 - V_Q}{2\sqrt{3} L_2} \frac{E_o + V_D + V_1 + V_2 - E_i}{E_o + V_D - V_Q} T \quad (12)$$

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11.18 GENERAL PHILOSOPHY OF SOLVING NONLINEAR SIMULTANEOUS EQUATIONS

Table 20 illustrates the different methods for solving simultaneous equations. The design equations are nonlinear constrained which shows the increase difficulty in performing the computer program.

After further review and working with TRW Systems Computer Department, a penalty function algorithms, Table 21, was used to solve the simultaneous equations. Each equation is solved as an unconstraint equation and its error value is determined and after iterative calculations, the solution coverges.

The Sequential Unconstrained Minimization Technique (SUMT) computer program developed by Research Analysis Corporation, McLean, Virginia, was used to solve the nonlinear constrained simultaneous equations. The program is basically a research tool and has many internal options depending on the nature of the equations to speed up the convergence to obtain a minimum solution.

SUMT is a computer program capable of minimizing a mathematical problem which has the following form:

$$\begin{aligned} &\text{Minimize} && f(x) \\ &\text{Subject to:} && g_j(x) \geq 0 && j = 1, 2, \dots, m \\ &&& h_j(x) = 0 && j = m+1, \dots, m+p = n \end{aligned}$$

$x = (x_1 \ x_2 \ \dots \ x_n)^T$ is a n -dimensional column vector.

Table 22 summarizes the functional designs solved by the SUMT Computer program. Hand calculations have been performed and the computer solution seems to be the minimum weight design in all cases. The computer option to speed up convergence of a solution can produce some unrealistic solutions. Continued work is needed to determine the correct option to solve the design equations.

METHODS TO SOLVE SIMULTANEOUS EQUATIONS

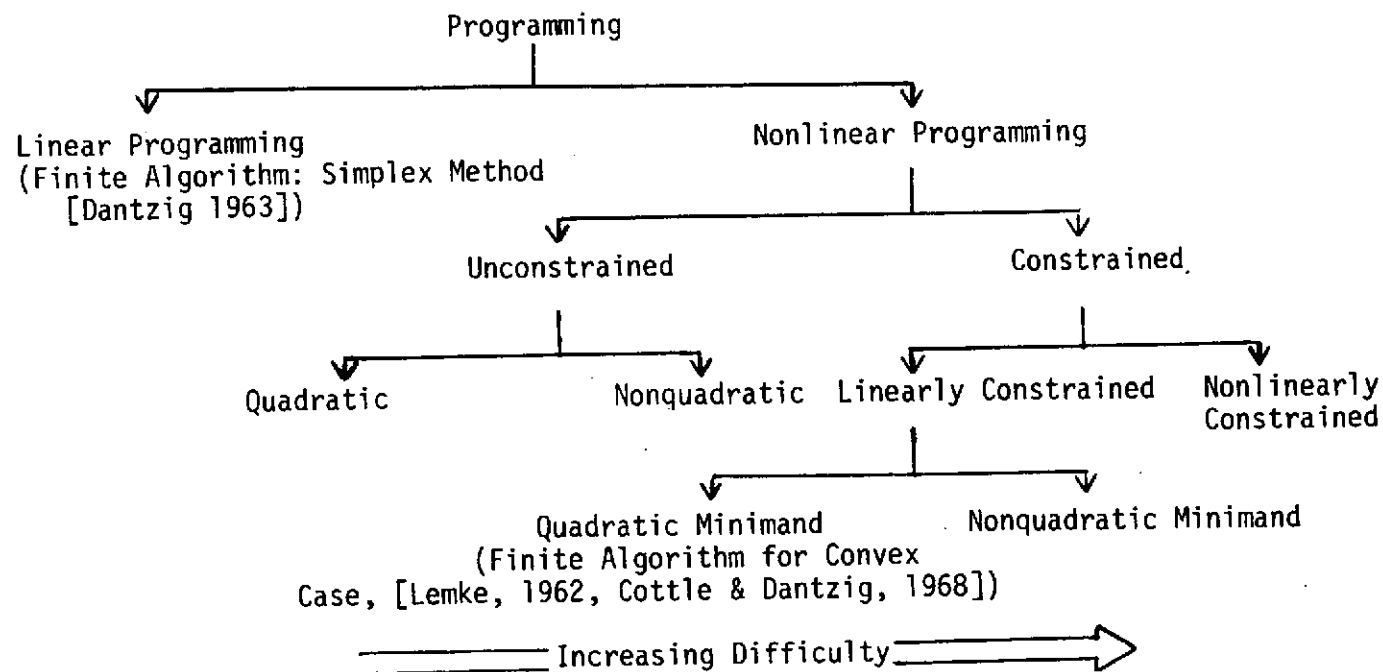


TABLE 20

METHODS TO SOLVE NONLINEAR CONSTRAINED EQUATIONS

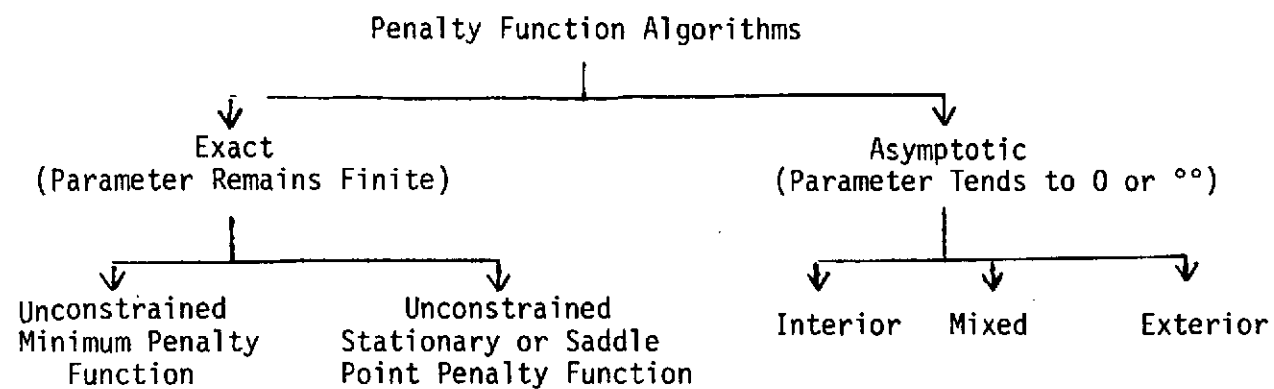


TABLE 21

FUNCTION DESIGN

- INDUCTOR

FILLED WINDOW	}	CONSTRAINTS
POWER LOSS		
CORE SATURATION		
WEIGHT - MINIMIZING		

- SINGLE-STAGE INPUT FILTER

FILLED WINDOW	}	CONSTRAINTS
CORE SATURATION		
ATTENUATION		
RESONANT PEAKING		
POWER LOSS		
WEIGHT - MINIMIZING		

- TWO-STAGE INPUT FILTER

FILLED WINDOW (2 CORES)	}	CONSTRAINTS
CORE SATURATION (2 CORES)		
ATTENUATION		
RESONANT PEAKING		
POWER LOSS		
WEIGHT - MINIMIZING		

The two-stage LC input filter is used as an example to show the computer solution and is contained in Appendix 11.19.

Effects on total weight due to changes in component parameters or design requirements can be easily made to determine relative sensitivity and to determine areas where great improvement can be obtained.

11.19 EXAMPLES OF SUMT APPLICATION IN OPTIMUM DESIGN

11.19.1 Single Stage LC Input Filter

A common element used in DC-DC Converter is an input filter to basically attenuate the switching current drawn by the switching regulation in order to eliminate any noise from being fed back into the primary power source.

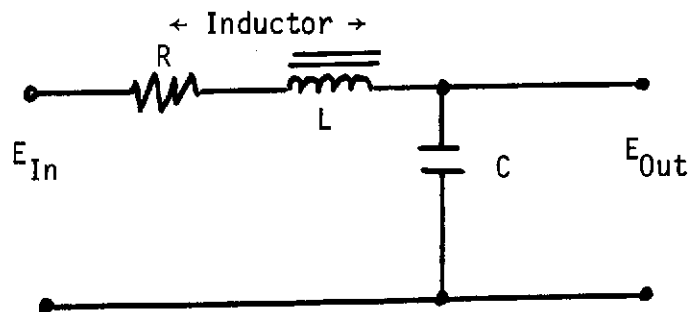


Figure 35. Schematic of Single Stage LC Input Filter

Figure 35 illustrates the basic schematic of a single stage LC input filter where L is the inductance value of the input choke, R is its winding resistance and C is the output capacitance value.

The first equation for the inductor assure that saturation does not occur.

$$B_s NA - L I_p = 0 \quad (1)$$

The second equation for the inductor is to insure that the window area of the toroidal core is completely filled in order to obtain an optimum design,

$$\left(\frac{1}{\pi FW}\right)^{1/2} (NA_C)^{1/2} - \frac{Z}{2\pi} + \frac{\sqrt{A}}{2} = 0 \quad (2)$$

The next design is to insure meeting the allocated power loss for the radiation.

$$4 \rho F_C N \sqrt{A} - R A_C = 0 \quad (3)$$

The attenuation characteristic of the filter must satisfy the electromagnetic interference requirements for the DC-DC converter at its basic switching frequency.

$$(1 - 4\pi^2 F^2 LC)^2 + 4\pi^2 F^2 R^2 C^2 - G^{-2} = 0 \quad (4)$$

where:

- K = Output capacitor density
- P = Resistivity of copper
- R = Winding resistance of the inductor
- Bs = Allowable flux of the iron core

The unknown values to be determined to optimize the design are:

- A = Iron core area
- Ac = Copper turn area
- L = Value of inductance
- C = Value of capacitance
- N = Number of turns for the inductor
- Z = Mean length of iron core.

Because of the complex nature of the equations, the close form solution can not be readily obtained using the LaGrange Multiplier technique, shown in Appendix 11.15. Computer optimization techniques must be used to solve for the minimum weight value.

All LC filters used in the power circuit of DC-DC converters are very efficient and therefore have very high Q factors when they are considered at their resonant frequency. Input ac disturbances will be amplified at the output terminals. The equation controlling this element is:

$$L - C (B \times R)^2 = 0 \quad (5)$$

The equation for the total weight of the single stage input is:

$$WT = 4F_c A_c D_c N \sqrt{A} + D_i A Z + KC \quad (6)$$

The known or specified values are:

- B = Peaking of value of filter
- G = Attenuation
- F = Operating frequency
- F_c = Winding factor
- F_w = Window fill factor
- I_p = Peak current in inductor
- D_c = Copper wire density
- D_i = Iron core density

11.19.2 Two Stage L-C Input Filter

Because of the difficulty in controlling the resonant peaking of the input filter and at the same time maintaining low losses, the two stage LC input filter has been developed and is being applied to new power conditioning equipment designs.

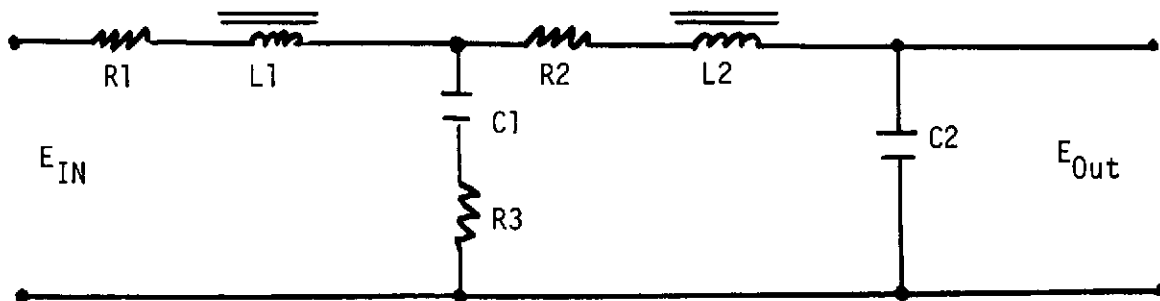


Figure 36. : Schematic of Two Stage LC Input Filter

Figure 36, illustrates the schematic of the two stage LC filter with internal damping to control resonant peaking without a penalty of power loss. Resistances R1 and R2 are winding resistances of L1 and L2.

The total resistance contributing to loss in the input filter is:

$$R = R1 + R2 = \rho \frac{4\sqrt{A_1} F_c N_1}{A_{c1}} + \rho \frac{4\sqrt{A_2} F_c N_2}{A_{c2}} \quad (7)$$

The resonant peaking of the first stage filter section is:

$$B^2 = \frac{1 + D^2}{\left(\frac{C_2}{C_1}\right)^2 + D^2 \left[1 - \frac{C_2}{C_1} - \frac{L_2}{L_1} \frac{C_2}{C_1}\right]^2} \quad (8)$$

The relation of the damping resistor R3 to the filter design is:

$$R3 = D \sqrt{\frac{L_1}{C_1}} \quad (9)$$

The relation to control the resonant peaking of the second stage section is:

$$\frac{L_2}{L_1} = K_R \quad (10)$$

The attenuation characteristic of the total two stage input filter is:

$$G = \left[\frac{L_2}{L_1} \frac{C_2}{C_1} \left(\frac{F}{f_1}\right)^3 \frac{1}{D} - \frac{C_2}{C_1} \left(\frac{F}{f_1}\right)^2 \right]^{-1} \quad (11)$$

The resonant frequency of the first stage section is:

$$f_1 = [2\pi \sqrt{L_1 C_1}]^{-1} \quad (12)$$

The design equations for the first stage inductor are:

$$B_s N_1 A_1 - L_1 I_p = 0 \quad (13)$$

and

$$\sqrt{\frac{N_1 A_{c1}}{\pi F_w}} - \frac{Z_1}{2\pi} + \frac{\sqrt{A_1}}{2} = 0 \quad (14)$$

The design equations for the second stage inductor are:

$$B_s N_2 A_2 - L_2 I_p = 0 \quad (15)$$

and

$$\sqrt{\frac{N_2 A_{c2}}{\pi F_w}} - \frac{Z_2}{2\pi} + \frac{\sqrt{A_2}}{2} = 0 \quad (16)$$

The total weight equation for the design is

$$\begin{aligned} W_T = & \underbrace{4F_c A_{c1} D_c N_1 \sqrt{A_1} + D_i A_1 Z_1}_{\leftarrow L_1 \text{ Weight} \rightarrow} \\ & + \underbrace{4F_c A_{c2} D_c N_2 \sqrt{A_2} + D_i A_2 Z_2}_{\leftarrow L_2 \text{ Weight} \rightarrow} \\ & + K_1 C_1 + K_2 C_2 + K_3 R_3 \end{aligned} \quad (17)$$

Capacitors & Resistor R3 weight

The known or specified values are:

- R = Total resistance of R_1 and R_2 for the two filter inductors
- ρ = Resistivity of the copper wire
- F = Switching frequency of the load current
- F_c = Winding factor
- F_w = Window fill factor
- B = Peaking value at resonance
- B_s = Maximum Flux density in magnetic cores
- G = Attenuation factor
- I_p = Peak current drawn load through inductors
- D_c = Specific gravity of copper
- D_i = Specific gravity of magnetic core
- K_R = Inductance ratio between L_1 and L_2
- K_1 = Density of capacitor C_1
- K_2 = Density of capacitor C_2
- K_3 = Density of resistor R_3

The unknown parameters that must be selected to minimize the total weight are:

- A_1 = Core area of first stage inductor
- A_{c1} = Copper area of winding in first stage inductor
- N_1 = Number of turns for first stage inductor
- Z_1 = Mean length of magnetic core for first stage inductor
- A_2 = Core area of second stage inductor
- A_{c2} = Copper area of winding in second stage inductor
- N_2 = Number of turns for second stage inductor
- Z_2 = Mean length of magnetic core for second stage inductor
- L_1 = Inductance value of first stage inductor
- L_2 = Inductance value of second stage inductor
- R_1 = Resistance of first stage inductor
- R_2 = Resistance of second stage inductor
- R_3 = Damping resistor in the first stage section

- C_1 = First stage capacitance value
- C_2 = Second stage capacitance value

There are 15 unknown parameters and 11 design constraint equations. Since this example represents the most complicated problem processed by the SUMT program, it is selected to illustrate the SUMT application in Section 11.19.3.

11.19.3 Computer Solution for Weight Optimization of a Two-Stage Input Filter

Equations (7) through (17), contained in Section 11.19.2, are the algebraic design equations for the two-stage LC input filter.

Table 23 shows the requirements and specified values of constants used in the design equations.

Table 24 is a list of unknown substitutions used in the computer programming. Table 25 is the list of constants used in the computer program. Table 26 is the list of design equations for programming.

Table 27 is the Fortran Program of the input data to SUMT Computer program.

Table 28 lists the results of three different designs based on the value of the second stage output filter capacitance value. Depending on the ac current rating of the capacitors and the derating policy for the design, different values would have to be used. The selection of the particular capacitor value to use will be computerized once a realistic data bank is established.

This problem was solved on a time-share remote terminal with a run cost between 20 to 35 dollars.

The design equation can be modified to minimize the total loss with a fixed weight, or a parametric curve can be generated that would show minimum weight as a function of loss with all other design parameters held constant.

RESULTS OF TWO-STAGE INPUT FILTER COMPUTER DESIGN

(Design Example)

A typical power processor filter design is made to test the characteristics of the SUIT program.

$P_o = 50W$	$P_i = 55W$	$F_c = 2$	<u>(ratio of mean length per turn</u>
$E_o = 15V$	$E_i = 20-50V$	$B_s = 0.4$	$\left[\frac{\text{Weber}}{m^2} \right]$ to circumference of core section
$R_o = 4.5 \Omega$		$I_p = 2.75 \text{ A}$	
$B = \text{Peaking} = \sqrt{2}$	$K_R = 1/3$ (Ratio of L_2/L_1)	$F_w = 0.4$	(Winding factor)
$P = 0.3W$	$K_1 = 372 \text{ Kg/F}$	$D_c = 8900$	(Spec. gravity of copper)
$R = 0.0396 \Omega$	$K_2 = 2600 \text{ Kg/F}$	$D_i = 7800$	(Spec. gravity of magn. core)
$G = 0.002$	(Attenuation)	$F = 20 \cdot 10^3$	(Switch Frequency)
$P = 1.724 \times 10^{-8}$			

TABLE 23

LIST OF SUBSTITUTIONS

The substitutions in the equations are:

$$\sqrt{A_1} = x_1$$

$$\sqrt{N_1} = x_2$$

$$\sqrt{Ac_1} = x_3$$

$$\sqrt{A_2} = x_4$$

$$\sqrt{N_2} = x_5$$

$$\sqrt{Ac_2} = x_6$$

$$L_1 = x_7$$

$$L_2 = x_8$$

$$C_1 = x_9$$

$$C_2 = x_{10}$$

$$Z_1 = x_{11}$$

$$Z_2 = x_{12}$$

$$R_1 = x_{13}$$

$$R_2 = x_{14}$$

$$D = x_{15}$$

$$f_1 = x_{16}$$

TABLE 24

LIST OF CONSTANTS

The constants are:

$$M1 = 4 FcDc$$

$$M2 = Di$$

$$M3 = 4 \sqrt{FZ}$$

$$M4 = 1/KR$$

$$M5 = 1/2 \pi$$

$$M6 = Ip/Bs$$

$$M7 = \sqrt{\frac{1}{\pi Fw}}$$

$$M8 = 0.5$$

$$C\phi 1 = R$$

$$C\phi 4 = B$$

$$C\phi 5 = G$$

$$C\phi 6 = F$$

TABLE 25

LIST OF DESIGN EQUATIONS

1. VAL = $[V13 + X14 - C01]$ C(1)
 2. VAL = $[M3 \times X1 \times X2^2 - X13 \cdot X3^2]$ C(2)
 3. VAL = $[M3 \cdot X4 \cdot X5^2 - X14 \cdot X6^2]$ C(3)
 4. VAL = $\left\{ \left(1 + X15^2 \right) X9^2 - C04 \left[X10^2 + X15^2 \left(X9 - X10 \left(1 + M4 \right) \right)^2 \right] \right\}$ C(4)
 5. VAL = $\left\{ M4 \cdot X10 \cdot C06^3 - X10 \cdot C06^2 \cdot X15 \cdot X16 - \frac{1}{C05} \cdot X16^3 \cdot X9 \cdot X15 \right\}$ C(5)
 6. VAL = $(X7 \cdot X9 \cdot X16^2 - M5^2)$ C(6)
 7. VAL = $(X1^2 \cdot X2^2 - X7 \cdot M6)$ C(7)
 8. VAL = $(X4^2 \cdot X5^2 - X8 \cdot M6)$ C(8)
 9. VAL = $[M7 \cdot X2 \cdot X3 - M5 \cdot X11 + M8 \cdot X1]$ C(9)
 10. VAL = $(M7 \cdot X5 \cdot X6 - M5 \cdot X12 + M8 \cdot X4)$ C(10)
 11. VAL = $(X8 - X7 \cdot KR)$ C(11)
 12. VAL = $(X10 - KC)$ C(12)
- O.F. $Wt = M1 \cdot X1 \cdot X2^2 \cdot X3^2 + M2 \cdot X1^2 \cdot X11 + K1 \cdot X9 + M1 \cdot X4 \cdot X5^2 \cdot X6^2 + M2 \cdot X4^2 \cdot X12$
 $V2 \cdot X10$

C(1) through C(12) are multipliers.

TABLE 26

FORTRAN PROGRAM

FORTRAN PROGRAM AS INPUT TO SUMT PROGRAM

```

00100 PROGRAM MAIN2 (DATA, OUTPUT, TAPES=DATA, TAPE6)
00110 C*   CONSTRAINED OPTIMIZATION USING SUMT
00120 C*
00130 C*   THIS VERSION IS A 16 VARIABLE PROBLEM WITH 12 CONSTRAINTS
00140 COMMON/CONS/VM1, VM2, VM3, VM4, VM5, VM6, VM7, VM8,
00150 1001, 004, 005, 006, XK1, XK2, XK3
00160 COMMON/INIT/XT(50)
00170 COMMON/SHAPE/X(100), DEL(100), A(100, 100), N, M, MN, NP1, NM1
00180 COMMON/CRST/ DELX(100), DELX0(100), RHOIN, RATIO, EPSI, THETA0,
00190 1 EPSI1, G1, X1(100), X2(100), X3(100), XR2(100), XR1(100), PPP,
00200 2 PR2, P1, F1, PJ1(100), DOTI, PGRAD(100), DIAG(100),
00210 3 PREV3, ADELX, NTCT0, NUMINT, NPHASE, USATIS
00220 COMMON/TIMES/TIMMAX
00230 COMMON /EQAL/ H, H1, H2
00240 COMMON /OPTNS/ NT1, NT2, NT3, NT4, NT5, NT6, NT7, NT8, NT9, NT10
00250 COMMON /EXOP1/ NEXOP1, NEXOP2, XEP1, XEP2
00260 COMMON/CONSTM/ C(20)
00270 REAL IP, K, L1, L2, K2, K3, KC
00280 NAMELIST/CONS/ B, G, FG, IP, DG, X, R, PHO, BS, FM, DI, F, KR, K2, KC
00290 NAMELIST/PR1/ EPSI, THETA0, RHOIN, RATIO, TIMMAX
00300 NAMELIST/OP1/ NT1, NT2, NT3, NT4, NT5, NT6, NT7, NT8, NT9, NT10
00310 NAMELIST/TOP/XEP1, XEP2, NEXOP1, NEXOP2
00320 NAMELIST/IN/ YI
00330 READ(5, CON)
00340 WRITE(6, CON)
00350 READ(5, PR1)
00360 WRITE(6, PR1)
00370 READ(5, OP1)
00380 WRITE(6, OP1)
00390 READ(5, TOP)
00400 WRITE(6, TOP)
00410 10 READ(5, IN)
00420 X1=XI(1)
00430 X2=XI(2)
00440 X3=XI(3)
00450 X4=XI(4)
00460 X5=XI(5)
00470 X6=XI(6)
00480 X7=XI(7)
00490 X8=XI(8)
00500 X9=XI(9)
00510 X10=XI(10)

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FORTRAN PROGRAM

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00520      X11=XI(11)
00530      X12=XI(12)
00540      X13=YI(13)
00550      X14=XI(14)
00560      X15=YI(15)
00570      Y16=XI(16)
00580      PT=3.141592654
00590      XM1=4.*FC*DC
00600      XM2=PI
00610      XM3=4.*PHO*FC
00620      YM4=1./KP
00630      XM5=1./(2.*PT)
00640      XM6=TP/RS
00650      XM7=SQRT(1./(PI*FM))
00660      YMA=.5
00670      XK1=X
00680      YK2=Y2
00690      YKC=KC
00700      C01=2
00710      C04=3
00720      C05=G
00730      C06=F
00740      IS1 = 0
00750      C(1)=X13+X14-C01
00760      C(2)=XM3*X1*X2*Y2-X13*X3**2
00770      C(3)=YM3*X4*Y5*Y6-Y14*Y6*Y6
00780      Y1=X9-X10*(1.+YM4)
00790      C(4)=(1.+X15*X15)*Y3*X9-C04*(X10**2+X15**2*Y1**2)
00800      Y1=YM4*Y11*C06**3
00810      Y2=-X10*C06**2*X15*X16
00820      Y3=-1./C05*X10**3*X9*X15
00830      C(5)=Y1+Y2+Y3
00840      C(6)=X7*X3*Y15**2-YM5**2
00850      C(7)=(X1*(2)**2-X7*XM6
00860      C(8)=(X4*Y5)**2-X8*YM6
00870      C(9)=XM7*(2*X3-YMC*X11+XM8*Y1
00880      C(10)=XM7*X5*Y6-XM5*X12+XM8*X4
00890      C(11)=X8-X7*YM4
00900      C(12)=Y10-YKC
00910      C(1)=1./C(1)
00920      C(2)=1./C(2)
00930      C(3)=1./C(3)

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FORTRAN PROGRAM

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00940 C(4)=1./C(4)
00950 C(5)=1./C(5)
00960 C(6)=1./C(6)
00970 C(7)=1./C(7)
00980 C(8)=1./C(8)
00990 C(9)=1./C(9)
01000 C(10)=1./C(10)
01010 C(11)=1./C(11)
01020 C(12)=1./C(12)
01030 WRITE(6,9035)
01040 DISPLAY(6)*C(1)=*,C(1),*C(2)=*,C(2),*C(3)=*,C(3),*C(4)=*,C(4)
01050 DISPLAY(6)*C(5)=*,C(5),*C(6)=*,C(6),*C(7)=*,C(7),*C(8)=*,C(8)
01060 DISPLAY(6)*C(9)=*,C(9),*C(10)=*,C(10),*C(11)=*,C(11)
01070 DISPLAY(6)*C(12)=*,C(12)
01080 9035 FORMAT(*0 THE CONSTANT MULTIPLIERS ARE*)
01090 WRITE(6,9030)
01100 9030 FORMAT(*0 CONSTANTS FOR THIS RUN*)
01110 WRITE(6,9040)YM1,XM2,YM3
01120 9040 FORMAT(* M1=*,G15.5,* M2=*,G15.5,* M3=*,G15.5)
01130 WRITE(6,9050)YM4,YM5,YM6
01140 9050 FORMAT(* M4=*,G15.5,* M5=*,G15.5,* M6=*,G15.5)
01150 WRITE(6,9060)YM7,XM8,XK1
01160 9060 FORMAT(* M7=*,G15.5,* M8=*,G15.5,* K=*,G15.5)
01170 WRITE(6,9070)XK2,C01,C04
01180 9070 FORMAT(* K2=*,G15.5,* C01=*,G15.5,* C04=*,G15.5)
01190 WRITE(6,9071)C05,C06,XKC
01200 9071 FORMAT(* C05=*,G15.5,* C06=*,G15.5,* KC=*,G15.5)
01210 WRITE(6,XIN)
01220 IST = IST + 1
01230 CALL SUMT(IST)
01240 IF(IST.EQ.1)GO TO 20
01250 WRITE(6,9001)IST
01260 9001 FORMAT(*0SUMT CONVERGED TO A SOLUTION FROM STARTING POINT*,I3)
01270 GO TO 30
01280 20 WRITE(6,9010)IST
01290 9010 FORMAT(*0 SUMT DID NOT CONVERGE TO A SOLUTION*,
01300 * FROM STARTING POINT*,I3)
01310 30 WRITE(6,9020)(X(I),I=1,16)
01320 TX1=X(1)*X(1)
01330 TX2=X(2)*X(2)
01340 TX3=X(3)*X(3)
01350 TX4=X(4)*X(4)

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FORTRAN PROGRAM

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01360      TX5=X(5)**2
01370      TX6=X(6)**2
01380      WRITE(6,9025)TX1,TX2,TX3,TX4
01390 9025 FORMAT(*0A1=*G15.5,* N1=*G15.5,* AC1=*G15.5,* A2=*G15.5)
01400      WRITE(6,9026)TX5,TX6,X(7),X(8)
01410 9026 FORMAT(*0A2=*G15.5,* AC2=*G15.5,* L1=*G15.5,* L2=*G15.5)
01420      WRITE(6,9027)X(9),Y(10),X(11),X(12)
01430 9027 FORMAT(*0C1=*G15.5,* C2=*G15.5,* Z1=*G15.5,* Z2=*G15.5)
01440      WRITE(6,9028)Y(13),Y(14),Y(15),Y(16)
01450 9028 FORMAT(*0R1=*G15.5,* R2=*G15.5,* D=*G15.5,* F1=*G15.5)
01460 9029 FORMAT(*0FINAL Y VALUES*/(1X,4F20.5))
01470      P3=Y(15)*SQRT(X(7)/X(9))
01480      DISPLAY*A1=*,TX1,*N1=*,TX2,*AC1=*,TX3
01490      DISPLAY*A2=*,TX4,*N2=*,TX5,*AC2=*,TX6
01500      DISPLAY*L1=*,X(7),*L2=*,X(8),*C1=*,Y(9)
01510      DISPLAY*C2=*,X(10),*Z1=*,X(11),*Z2=*,X(12)
01520      DISPLAY*P1=*,Y(13),*R2=*,Y(14),*D=*,X(15)
01530      DISPLAY*F1=*,Y(16),*P3=*,P3
01540      GO TO 10
01550      END
01560      SUBROUTINE READPR
01570      COMMON/SHARE/X(100),DEL(100),A(100,100),N,M,MN,NP1,NM1
01580      COMMON/FOAL/H,M1,M7
01590      COMMON/INIT/XT(50)
01600      ENTRY P50
01610      M=0
01620      N=16
01630      MZ=12
01640      RETURN
01650      ENTRY P60
01660      DO 11 I=1,N
01670 10 X(I)=XI(I)
01680      RETURN
01690      ENTRY P80
01700      RETURN
01710      ENTRY P601
01720      RETURN
01730      ENTRY P801
01740      RETURN
01750      ENTRY PUNCH
01760      RETURN
01770      END

```

FORTRAN PROGRAM

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01780 SUBROUTINE RESTNT(I1,VAL)
01790 C THIS SUBROUTINE EVALUATES THE O.F. IF I=0
01800 C OR THE CONSTRAINT II IF II NOT EQUAL TO 0
01810 COMMON/SHARE/X(100),DEL(100),A(100,100),N,M,MN,MP1,NM1
01820 COMMON/CONS/YM1,YM2,YM3,YM4,YM5,YM6,YM7,YM8,C01,C04,C05,C06,
01830 1XK1,XK2,XK3
01840 COMMON/CONSTM/C(20)
01850 EQUIVALENCE (X1,Y(1)),(Y2,Y(2)),(X3,Y(3)),(Y4,X(4)),
01860 C(X5,Y(5)),(Y6,Y(6)),(X7,X(7)),(X8,Y(8)),(Y9,X(9)),
01870 C(X10,X(10)),(X11,X(11)),(X12,X(12)),(X13,X(13)),(X14,X(14))
01880 EQUIVALENCE (Y15,Y(15)),(Y16,X(16))
01890 II=I1+1
01900 GO TO (1000,1,2,3,4,5,6,7,8,9,10,11,12),II
01910 C EVALUATE O.F.
01920 1000 Y1=YM1*Y1*X2*Y2*X3**2
01930 Y2=YM2*X1**2*X11
01940 Y3=Y41*X9
01950 Y4=YM1*Y4*X5*X5*X6*X6
01960 Y5=Y42*X4*X4*X12
01970 Y6=YK2*Y17
01980 VAL=Y1+Y2+Y3+Y4+Y5+Y6
01990 RETURN
02000 C EVAL.CONSTR.1
02010 1 VAL=(Y13+X14-C01)*C(1)
02020 RETURN
02030 C EVAL.CONSTR.2
02040 2 VAL=(YM3*X1*X2*Y2-Y13*X3**2)*C(2)
02050 RETURN
02060 C EVAL.CONSTR.3
02070 3 VAL=(YM3*X4*X5*X5-Y14*X6**2)*C(3)
02080 RETURN
02090 C EVAL.CONSTR.4
02100 4 Y1=X7-X10*(1.+XM4)
02110 VAL=(1.+X15*X15)*Y2**2-C04*(X10**2+X15**2*Y1**2)
02120 VAL=VAL*C(4)
02130 RETURN
02140 C EVAL.CONSTR.5
02150 5 Y1=YM4*X11*C06**3
02160 Y2=-X10*C06**2*Y15*X16
02170 Y3=-1./C05*Y16**3*X9*X15
02180 VAL=(Y1+Y2+Y3)*C(5)
02190 RETURN

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FORTRAN PROGRAM

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02200 C      EVAL.CONSTR.6
02210      6 VAL=(X7*X9*X15**2-X*Y5**2)*C(6)
02220      RETURN
02230 C      EVAL.CONSTR.7
02240      7 VAL=((X1*X2)**2-X7*X*Y6)*C(7)
02250      RETURN
02260 C      EVAL.CONSTR.8
02270      8 VAL=((X4*X5)**2-X8*X*Y6)*C(8)
02280      RETURN
02290 C      EVAL.CONSTR.9
02300      9 VAL=(X*Y7*X2*X3-X*Y5*X11+X*Y8*X1)*C(9)
02310      RETURN
02320 C      EVAL.CONSTR.10
02330      10 VAL=(X*Y7*X5*X4-X*Y5*X12+X*Y8*X4)*C(10)
02340      RETURN
02350      11 VAL=(X8-X7*X*Y4)*C(11)
02360      RETURN
02370      12 VAL=(X10-X*Y4)*C(12)
02380      RETURN
02390      END
02400      SUBROUTINE GRAD1(II)
02410 C      THIS SUBROUTINE EVALUATES THE GRADIENT OF THE
02420 C      O.F. IF II=0 OR OF CONSTRAINT II
02430      COMMON/SHAPE/Y(100),DEL(100),A(100,100),N,M,MN,NP1,NM1
02440      COMMON/CONS/XM1,XM2,XM3,XM4,XM5,XM6,XM7,XM8,C01,C04,C05,C06,
02450      1XK1,XK2,XK3
02460      COMMON/CONSTH/C(20)
02470      EQUIVALENCE (X1,X(1)),(X2,X(2)),(X3,X(3)),(X4,X(4)),(X5,X(5)),
02480      C(X6,X(6)),(X7,X(7)),(X8,X(8)),(X9,X(9)),(X10,X(10)),
02490      C(X11,X(11)),(X12,X(12)),(X13,X(13)),(X14,X(14))
02500      EQUIVALENCE (X15,X(15)),(X16,X(16))
02510      IT=II+1
02520      DO 50 I=1,16
02530      50 DEL(I)=0.
02540      GO TO (100,1,2,3,4,5,6,7,8,9,10,11,12),IT
02550 C      EVAL.GRAD.OF O.F.
02560      100 DEL(1)=Y*Y1*(X2*Y3)**2+2.*X*Y2*X1*Y11
02570      DEL(2)=2.*X*Y1*Y1*X2*Y3*Y3
02580      DEL(3)=2.*X*Y1*X1*Y2*X2*Y3
02590      DEL(4)=X*Y1*(X5*Y6)**2+2.*X*Y2*X4*Y12
02600      DEL(5)=2.*X*Y1*X4*Y5*Y6*Y6
02610      DEL(6)=2.*X*Y1*X4*Y5*Y5*Y6

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FORTRAN PROGRAM

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02620 DEL(9)=XK1
02630 DEL(10)=XK2
02640 DEL(11)=XK2*Y1*Y1
02650 DEL(12)=XK2*Y4*Y4
02660 RETURN
02670 C EVAL GRAD. OF CONSTP.1
02680 1 DEL(13)=1.*C(1)
02690 DEL(14)=1.*C(1)
02700 RETURN
02710 C EVAL GRAD. OF CONSTP.2
02720 2 DEL(1)=XK3*X2**2*C(2)
02730 DEL(2)=2.*XK3*X1*Y2*C(2)
02740 DEL(3)=-2.*Y3*X13*C(2)
02750 DEL(13)=-X3**2*C(2)
02760 RETURN
02770 C EVAL GRAD. OF CONSTP.3
02780 3 DEL(4)=XK3*Y5*X5*C(3)
02790 DEL(5)=2*YK3*X4*X5*C(3)
02800 DEL(6)=-2.*X6*Y14*C(3)
02810 DEL(14)=-Y6**2*C(3)
02820 RETURN
02830 C EVAL GRAD. OF CONSTP.4
02840 4 Y1=1.+X15**2
02850 Y2=X9-Y10*(1.+YK4)
02860 DEL(9)=(2.*Y3*Y1-2.*C04*X15**2*Y2)*C(4)
02870 DEL(10)=(-2.*C04*X10+2.*X15**2*Y2*(1.+YK4)*C04)*C(4)
02880 DEL(15)=(2.*Y2**2*X15-2.*C04*X15*Y2**2)*C(4)
02890 RETURN
02900 C EVAL GRAD. OF CONSTP.5
02910 5 DEL(9)=-X15*Y16**3/C05*C(5)
02920 DEL(10)=(XK4*C06**3-C06**2*Y15*X16)*C(5)
02930 DEL(15)=(-X10*C06**2*X16-Y16**3*X9/C05)*C(5)
02940 DEL(16)=(-X10*C06**2*X15-3.*X16**2*X15*X9/C05)*C(5)
02950 RETURN
02960 C EVAL GRAD. OF CONSTP.6
02970 6 Y1=Y16**2
02980 DEL(7)=X9*Y1*C(6)
02990 DEL(9)=X7*Y1*C(6)
03000 DEL(16)=2.*X7*X9*X16*C(6)
03010 RETURN
03020 C EVAL GRAD. OF CONSTP.7
03030 7 DEL(1)=2.*X1*Y2**2*C(7)

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FORTRAN PROGRAM

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03040 DEL(2)=2.*Y1*Y1*X2*C(7)
03050 DEL(7)=-X46*C(7)
03060 RETURN
03070 C EVAL.GRAD.OF CONSTE.3
03080 3 Y1=2.*X4*X5
03090 DEL(4)=Y1*X5*C(8)
03100 DEL(5)=Y1*X4*C(8)
03110 DEL(8)=-X46*C(8)
03120 RETURN
03130 C EVAL.GRAD.OF CONSTE.3
03140 3 DEL(1)=Y48*C(9)
03150 DEL(2)=Y47*X3*C(9)
03160 DEL(3)=X2*Y47*C(9)
03170 DEL(11)=-X45*C(9)
03180 RETURN
03190 C EVAL.GRAD.OF CONSTE.10
03200 10 DEL(4)=Y48*C(10)
03210 DEL(5)=Y47*X5*C(10)
03220 DEL(6)=X47*Y5*C(10)
03230 DEL(12)=-X45*C(10)
03240 RETURN
03250 11 DEL(7)=-X44*C(11)
03260 DEL(8)=C(11)
03270 RETURN
03280 12 DEL(10)=C(12)
03290 RETURN
03300 END
03310 SUBROUTINE MATRIX(II,1)
03320 C EVALUATES THE SECOND PARTIALS OF THE O.F. IF II=3
03330 C OR CONSTRAINT II IF II NOT 1
03340 COMMON/CHARE/X(100),DEL(100),A(100,100),N,M,MN,NP1,NM1
03350 COMMON/CONS/YM1,YM2,XM3,XM4,XM5,XM6,XM7,XM8
03360 1001,C04,C05,C06,XK1,XK2,XK3
03370 COMMON/CONSTM/C(20)
03380 EQUIVALENCE(X1,X(1)),(X2,X(2)),(X3,X(3)),(X4,X(4)),(X5,X(5)),
03390 1(X6,X(6)),(X7,X(7)),(X8,X(8)),(X9,X(9)),(X10,X(10)),
03400 2(X11,X(11)),(X12,X(12)),(X13,X(13)),(X14,X(14)),(X15,X(15)),
03410 3(Y16,Y(16))
03420 IF=II+1
03430 GO TO (100,1,2,3,4,5,6,7,8,9,10,11,12),IF
03440 C O.F.
03450 100 A(1,1)=2.*XM2*X11

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FORTRAN PROGRAM

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03455 A(1,2)=2.*XM1*X2*X3**2
03470 A(1,3)=2.*XM1*X2**2*X3
03480 A(1,11)=2.*XM2*X1
03490 A(2,2)=2.*XM1*X1*X3**2
03500 A(2,3)=4.*XM1*X1*X2*X3
03510 A(3,3)=2.*XM1*X1*X2**2
03520 A(4,4)=2.*XM2*X12
03530 A(4,5)=2.*XM1*X5*X6**2
03540 A(4,6)=2.*XM1*X5**2*X6
03550 A(4,12)=2.*XM2*X4
03560 A(5,5)=2.*XM1*X4*X5*X6
03570 A(5,6)=4.*XM1*X4*X5*X6
03580 A(6,6)=2.*XM1*X4*X5**2
03590 RETURN
03600 C CONSTP.1
03610 1 L=1
03620 RETURN
03630 C CONSTP.2
03640 2 A(1,2)=2.*XM3*C(2)*X2
03650 A(2,2)=2.*XM3*X1*C(2)
03660 A(3,3)=-2.*X13*C(2)
03670 A(3,13)=-2.*X3*C(2)
03680 RETURN
03690 C CONSTP.3
03700 3 A(4,5)=2.*XM3*C(3)*X5
03710 A(5,5)=2.*XM3*X4*C(3)
03720 A(6,6)=-2.*X14*C(3)
03730 A(6,14)=-2.*X6*C(3)
03740 RETURN
03750 C CONSTP.4
03760 4 Y1=1.+X15**2
03770 Y2=X9-X10*(1.+XM4)
03780 A(9,9)=(2.*Y1-2.*C04*X15**2)*C(4)
03790 A(9,10)=(2.*C04*X15**2*(1.+XM4))*C(4)
03800 A(9,15)=(4.*Y9*X15-4.*C04*X15*Y2)*C(4)
03810 A(10,10)=(-2.*C04-2.*X15**2*(1.+XM4)**2*C04)*C(4)
03820 A(10,15)=(4.*X15*Y2*(1.+XM4)*C04)*C(4)
03830 A(15,15)=(2.*X9**2-2.*C04*Y2**2)*C(4)
03840 RETURN
03850 C CONSTP.5
03860 5 A(9,15)=-X15**3/C05*C(5)
03870 A(9,16)=-3.*Y15*X16**2/C05*C(5)

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FORTRAN PROGRAM

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03880      A(10,15)=-C06**2*X16*C(5)
03890      A(10,16)=-C06**2*X15*C(5)
03900      A(15,16)=(-Y1*C06**2-3.*Y16**2*X9/C05)*C(5)
03910      A(16,16)=-6.*Y16*X15*X9/C05*C(5)
03920      RETURN
03930 C      CONSTP.6
03940      6 Y1=X15**2
03950      A(7,9)=Y1*C(6)
03960      A(7,16)=2.*X9*X16*C(6)
03970      A(9,16)=2.*Y7*X16*C(6)
03980      A(16,16)=2.*Y7*X9*C(6)
03990      RETURN
04000 C      CONSTP.7
04010      7 A(1,1)=2.*Y2**2*C(7)
04020      A(1,2)=4.*X1*Y2*C(7)
04030      A(2,2)=2.*X1**2*C(7)
04040      RETURN
04050 C      CONSTP.8
04060      8 A(4,4)=2.*X5**2*C(8)
04070      A(4,5)=4.*X4*Y5*C(8)
04080      A(5,5)=2.*X4**2*C(8)
04090      RETURN
04100 C      CONSTP.9
04110      9 A(2,3)=Y7*C(9)
04120      RETURN
04130 C      CONSTP.10
04140      10 A(5,6)=Y7*C(10)
04150      RETURN
04160      11 L=1
04170      RETURN
04180      12 L=1
04190      RETURN
04200      END

```

COMPUTER SOLUTIONS

		RUN I Kc = 20 μ F	RUN II Kc = 10 μ F	RUN III Kc = 40 μ F
A1	= X1 ² =	43.83 10 ⁻⁶	47.86 10 ⁻⁶	24.12 10 ⁻⁶
N1	= X2 ² =	29.04	29.76	25.03
Ac1	= X3 ² =	0.964 10 ⁻⁶	1.028 10 ⁻⁶	0.616 10 ⁻⁶
A2	= X4 ² =	25.23 10 ⁻⁶	23.15 10 ⁻⁶	13.68 10 ⁻⁶
N2	= X5 ² =	16.82	20.51	14.72
Ac2	= X6 ² =	0.971 10 ⁻⁶	1.144 10 ⁻⁶	0.625 10 ⁻⁶
L1	= X7 =	185.19 10 ⁻⁶	207.19 10 ⁻⁶	87.85 10 ⁻⁶
L2	= X8 =	61.73 10 ⁻⁶	69.06 10 ⁻⁶	29.28 10 ⁻⁶
C1	= X9 =	71.68 10 ⁻⁶	75.55 10 ⁻⁶	67.5 10 ⁻⁶
C2	= X10 =	20.00 10 ⁻⁶	10.00 10 ⁻⁶	40.00 10 ⁻⁶
Z1	= X11 =	50.46 10 ⁻³	52.73 10 ⁻³	37.45 10 ⁻³
Z2	= X12 =	38.43 10 ⁻³	42.27 10 ⁻³	28.62 10 ⁻³
R1	= X13 =	27.57 10 ⁻³	27.68 10 ⁻³	27.56 10 ⁻³
R2	= X14 =	12.03 10 ⁻³	11.91 10 ⁻³	12.03 10 ⁻³
D	= X15 =	1.09	0.737	0.7
f1	= X16 =	1.331 10 ³	1.272 10 ³	2.066 10 ³
R3	= D $\sqrt{\frac{L1}{C1}}$ =	1.75	1.22	0.80
Weight	=	122.5 gr.	104.5 gr.	147.0 gr.

TABLE 28

11.20 FORMULATION OF MATHEMATICAL EQUATION FOR A SERIES SWITCHING BUCK REGULATOR

Subsequent to the development of the design equations for a two-stage input filter, contained in Appendix 11.19, the next logical step is to develop the generalized design equations for the series switching buck regulator.

Figure 37 illustrates the basic schematic of the power stage, which includes the two-stage input filter, power switch Q, commutating diode D, and output filter.

Equations (1) through (6) list the total loss for the total power stage including all inductors, capacitors, transistors and diodes. The nature of the losses includes core loss, copper loss, steady state conduction loss, and switching losses.

Equation (7) controls the resonant peaking of the two-stage input filter.

Equation (8) determines the attenuation of the two-stage input filter. Notice the design of the output filter inductor enters clearly eq. (8). The three basic requirements in equation (8) are: (1) the EMI requirement, (2) the switch current being impressed on the output of the input filter and (3) the filter attenuation characteristic.

Equation (9) determines the first-stage resonant frequency.

Equation (10) through (15) control the design of the three filter inductors used in the power stage. The design constraints are filled window and free from saturation.

Equation (16) determines the ripple appearing at the output terminals of the power stage.

Equation (17) relates the series resistance in the output filter capacitor to the value of the capacitor.

POWER PROCESSOR DESIGN EQUATIONS

a) SERIES BUCK REGULATOR SCHEMATIC

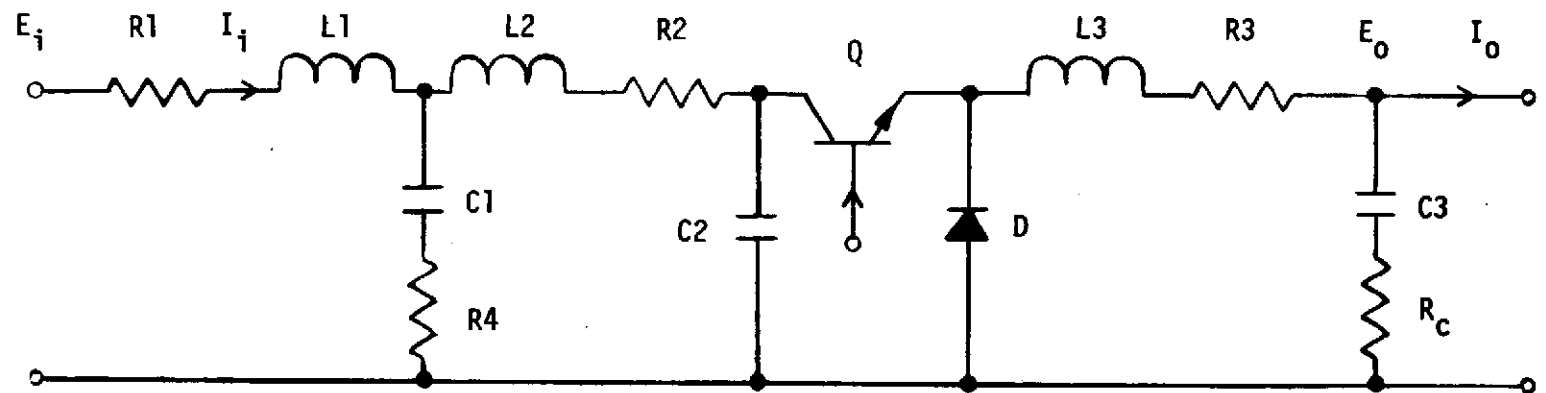


Figure 37.

Equation (18) determines the ac current in the second stage capacitor C_2 of the two stage input filter.

Equation (19) is the total weight of the total power stage for the series switch buck regulator.

Two more additional design constraint equations need to be written to include the effect of the feedback control system to determine output impedance and line rejection characteristics of the power stage. Additional development is necessary to develop these design equations.

The known or specified values are:

- P_o = Output power
- e = Total efficiency of power stage
- E_i = Input voltage
- E_o = Output voltage
- F_c = Winding factor
- F_w = Window fill factor
- ρ = Resistivity of copper wire
- V_{ST} = Transistor collector-emitter saturated drop
- V_{bet} = Transistor base emitter voltage drop
- T_{snt} = Transistor switching turn-on time
- T_{sft} = Transistor switching turn off time
- V_D = Diode forward drop
- T_{snd} = Diode turn on time
- T_{sfd} = Diode turn off time
- T_{re} = Diode recovery time
- $O_{er(F)}$ = Core loss factor for output filter inductor L_3
- $(PE)_1$ = Peaking value of two stage filter
- $(PE)_2$ = Ratio of L_2 to L_1 inductance
- B_{s1}, B_{s2}, B_{s3} = Operating flux density of the three inductors
- r = Output ripple
- R_{ck} = ESR per tube of output capacitance C_3
- C_k = Microfarads per tube of output capacitance in C_3
- D_i = Specific gravity of magnetic core
- D_c = Specific gravity of copper wire
- K_{c1}, K_{c2}, K_{c3} = Density of capacitors C_1, C_2 and C_3
- K_{R4} = Weight of damping resistor R_4 .

The unknown parameters that must be selected to minimize the total weight are:

- A_1, A_2, A_3 = Core area of the three inductors
- A_{c1}, A_{c2}, A_{c3} = Copper area of the winding of the three inductors
- N_1, N_2, N_3 = Number of turns for the three inductors
- Z_1, Z_2, Z_3 = Mean length of the magnetic cores of the three inductors
- L_1, L_2, L_3 = Inductance value of the three inductors
- R_1, R_2, R_3 = Resistance of the winding of the three inductors
- R_4 = Capacitor C_1 damping resistor
- F = Switching frequency
- R_c = Output filter series resistance
- D = Damping of input filter
- C_1, C_2, C_3 = Capacitance values
- f_1 = Resonant frequency of first stage of input filter
- I_{ac} = RMS current in capacitor C_2 of the input filter

These equations demonstrates the manner in defining the characteristics of the series switch buck regulator.

These equations have not been checked by the optimization program which can be performed in the next phase.

In this example there are 27 unknown parameters and 14 design constraints. The computer optimization program used to solve the previous set of equations for the inductor single stage filter and two stage filter can handle up to 100 unknown parameters and therefore should be capable of solving these design equations to obtain a minimum weight design.

b) DESIGN EQUATIONS

- Input Filter Loss:

$$(1) \quad P_{Lf} = \left(\frac{P_o}{e E_i} \right)^2 \left(\frac{\overset{\text{Winding Resistance of } L_1}{4 F_c N_1 \sqrt{A_1} P}}{A_{c1}} + \frac{\overset{\text{Winding Resistance of } L_2}{4 F_c N_2 \sqrt{A_2} P}}{A_{c2}} \right) \quad (1)$$

- Transistor Loss:

$$(2) \quad P_{TQ} = \left(\frac{\overset{\text{Saturated Drop}}{P_o V_{st}}}{E_i} + \frac{\overset{\text{Base Drive}}{0.1 P_o V_{bet}}}{E_i} \right) + \frac{\overset{\text{Transistor Turn-on Switching}}{E_i \left[\frac{P_o}{E_o} - \frac{(E_i - E_o) E_o}{2 L_3 E_i F} \right] T_{snt} F}}{6} + \frac{\overset{\text{Transistor Turn-off Switching}}{E_i \left[\frac{P_o}{E_o} + \frac{(E_i - E_o) E_o}{2 L_3 E_i F} \right] T_{sft} F}}{6} \quad (2)$$

- Diode Loss:

$$(3) \quad P_d = \frac{\overset{\text{Forward Conduction}}{(E_i - E_o) P_o V_o}}{E_o E_i} + \frac{\overset{\text{Diode Recovery and Turn-off}}{E_i F \left[\frac{P_o}{E_o} - \frac{(E_i - E_o) E_o}{2 L_3 E_i F} \right] \{ T_{sfd} + 3 T_{re} \}}}{12} + \frac{\overset{\text{Diode Turn-on}}{E_i F \left[\frac{P_o}{E_o} + \frac{(E_i - E_o) E_o}{2 L_3 E_i F} \right] T_{snd}}}{12} \quad (3)$$

- Output Filter Inductor Loss:

$$(4) \quad P_{ofi} = \frac{80 E_o (E_i - E_o)^{3/2} O_{er}(F)}{N_3 E_i} \quad (\text{Core}) \quad (4)$$

$$+ \left\{ \left(\frac{P_o}{E_o} \right)^2 + \left[\frac{(E_i - E_o) E_o}{12 L E_i F} \right]^2 \right\} \rho \frac{4 F_c N_3 \sqrt{A_3}}{A_{c3}} \quad (\text{Copper})$$

- Output Filter Capacitor Loss:

$$(5) \quad P_{oc} = \frac{1}{12} \left[\frac{(E_i - E_o) E_o}{12 L E_i F} \right]^2 R_c \quad (5)$$

Constraints: (Total Power Loss)

$$(6) \quad P_{it} + P_c + P_d + P_{ofi} + P_{oc} = P_i \quad (6)$$

Constraints:

- Input Filter Peaking: (PE)

$$(7) \quad (PE)_1^2 = \frac{1+D^2}{\left(\frac{C_2}{C_1}\right)^2 + D^2 \left[1 - \frac{C_2}{C_1} - \frac{L_2 C_2}{L_1 C_1}\right]^2} \quad (7A)$$

First Stage

$$\text{Second Stage} \quad (PE)_2 = \frac{L_2}{L_1} \quad (7B)$$

- Input Filter Attenuation:

$$(8) \quad \frac{\frac{0.5}{\sqrt{1+\left(\frac{F}{2\alpha\omega}\right)^2}} \text{ (EMI Requirement)}}{\sqrt{\left(\frac{2P_o}{\pi E_o} \sin \frac{\pi E_o}{E_i}\right)^2 + \left[\frac{1}{LF} \cdot \frac{(E_i - E_o)E_o}{\pi E_i} \left(\cos \frac{\pi E_o}{E_i} - \frac{\sin \frac{\pi E_o}{E_i}}{\frac{\pi E_o}{E_i}}\right)\right]^2}} = \frac{1}{\frac{L_2 C_2}{L_1 C_1} \left(\frac{F}{f_1}\right)^3 \frac{1}{D} - \frac{C_2}{C_1} \left(\frac{F}{f_1}\right)^2} \text{ (Filter Design Value)} \quad (8)$$

(Switch Current)

$$(9) \quad f_1 = \frac{1}{2\pi \sqrt{L_1 C_1}} \text{ (First Stage Resonant Frequency)} \quad (9)$$

- L_1 (Filled Window)

$$(10) \quad \sqrt{\frac{A_{c1} N_1}{\pi F_w}} - \frac{\gamma_1}{2\pi} + \frac{\sqrt{A_1}}{2} = 0 \quad (10)$$

- L_1 Saturation

$$(11) \quad N_1 A_1 - \frac{L_1 \left(\frac{P_0}{e E_1} \right)}{B_{s1}} = 0 \quad (11)$$

- L_2 (Filled Window)

$$(12) \quad \sqrt{\frac{A_{c2} N_2}{\pi F_w}} - \frac{\gamma_2}{2\pi} + \frac{\sqrt{A_2}}{2} = 0 \quad (12)$$

- L_2 Saturation

$$(13) \quad N_2 A_2 - \frac{L_2 \left(\frac{P_0}{e E_1} \right)}{B_{s2}} = 0 \quad (13)$$

- L_3 (Filled Window)

$$(14) \quad \sqrt{\frac{A_{c3} N_3}{\pi F_w}} - \frac{\gamma_3}{2\pi} + \frac{\sqrt{A_3}}{2} = 0 \quad (14)$$

- L_3 Saturation

$$(15) \quad N_3 A_3 - \frac{L_3 \left[\frac{P_0}{E_0} + \frac{(E_i - E_0) E_0}{2 L E_i F} \right]}{B_{s3}} = 0 \quad (15)$$

- Converter Output Ripple r in % of E_0

$$(16) \quad \frac{1}{8 L_3 C_3} \left(1 - \frac{E_0}{E_i} \right) \left[\left(\frac{1}{F} \right)^2 + \frac{4 C_3^2 R_c^2 E_i^2}{E_0 (E_i - E_0)} \right] = r \quad (16)$$

- Relationship of R_c to C_3

$$(17) \quad \frac{C_3 R_{CK}}{C_K} = R_c \quad (17)$$

C_K : μF per Tube
 R_{CK} : ESR per Tube

- Relationship of C_2 to $(I_{rms})_{ac}$ in Q

$$(18) \quad (I_{ac})_{rms} \text{ in } C_2 = \frac{E_o}{E_i} \left\{ \left(\frac{P_o}{E_o} \right)^2 + \frac{1}{12} \left[\frac{(E_i - E_o)E_o}{L E_i F} \right]^2 \right\} - \frac{P_o^2}{E_i^2} \quad (18)$$

$$\therefore C_2 \geq (I_{ac})_{rms} \cdot K_{C2}$$

K_{C2} is $\mu F/rms. \text{ Amp.}$

Wt. to be Optimized:

Iron Weight for L_1, L_2 and L_3

Copper Weight for L_1, L_2 and L_3

$$D_i [A_1 z_1 + A_2 z_2 + A_3 z_3] + 4 F D_c [A_{c1} N_1 \sqrt{A_1} + A_{c2} N_2 \sqrt{A_2} + A_{c3} N_3 \sqrt{A_3}]$$

1st Stage
Capacitor
Weight

2nd Stage
Capacitor
Weight

3rd Stage
Capacitor
Weight

1st Stage
Damping
Resistor
Weight

$$+ K_{c1} C_1 + K_{c2} C_2 + K_{c3} C_3 + K_{RA}$$

(19)

11.21 AN EXAMPLE OF POWER PROCESSING EQUIPMENT COMPUTER SIMULATION USING TESS PROGRAM

This section describes the simulation of a chopper regulator using the TESS transient computer program. This program accepts nonlinear elements (diodes, transistors) as well as mathematical expressions. The circuit is shown in Figure 38(A). The power stage is simulated with the Transistor T1 and Diode D1. The control loops are simulated using the operational amplifier A2 and A3. A1 establishes the reference frequency for the system. The voltage source EB is controlled by a subroutine FEB which is a function of the voltages VRC and VRTH. A timing diagram is shown in Figure 38(B).

The simulation has been made specifying the integration routine "GEAR." This routine has the ability to control the step size with little dependence on the circuit time constant, making it very fast and efficient. One run has been made over a 300 microsecond period.

The TESS program allows the user to specify models of semiconductors. They can be generated by the user or they might be available through a library data bank. The description of the three models used in this program is given below:

POWER PROCESSOR SIMULATION SERIES CHOPPER - CONSTANT FREQUENCY - CLOCK ON

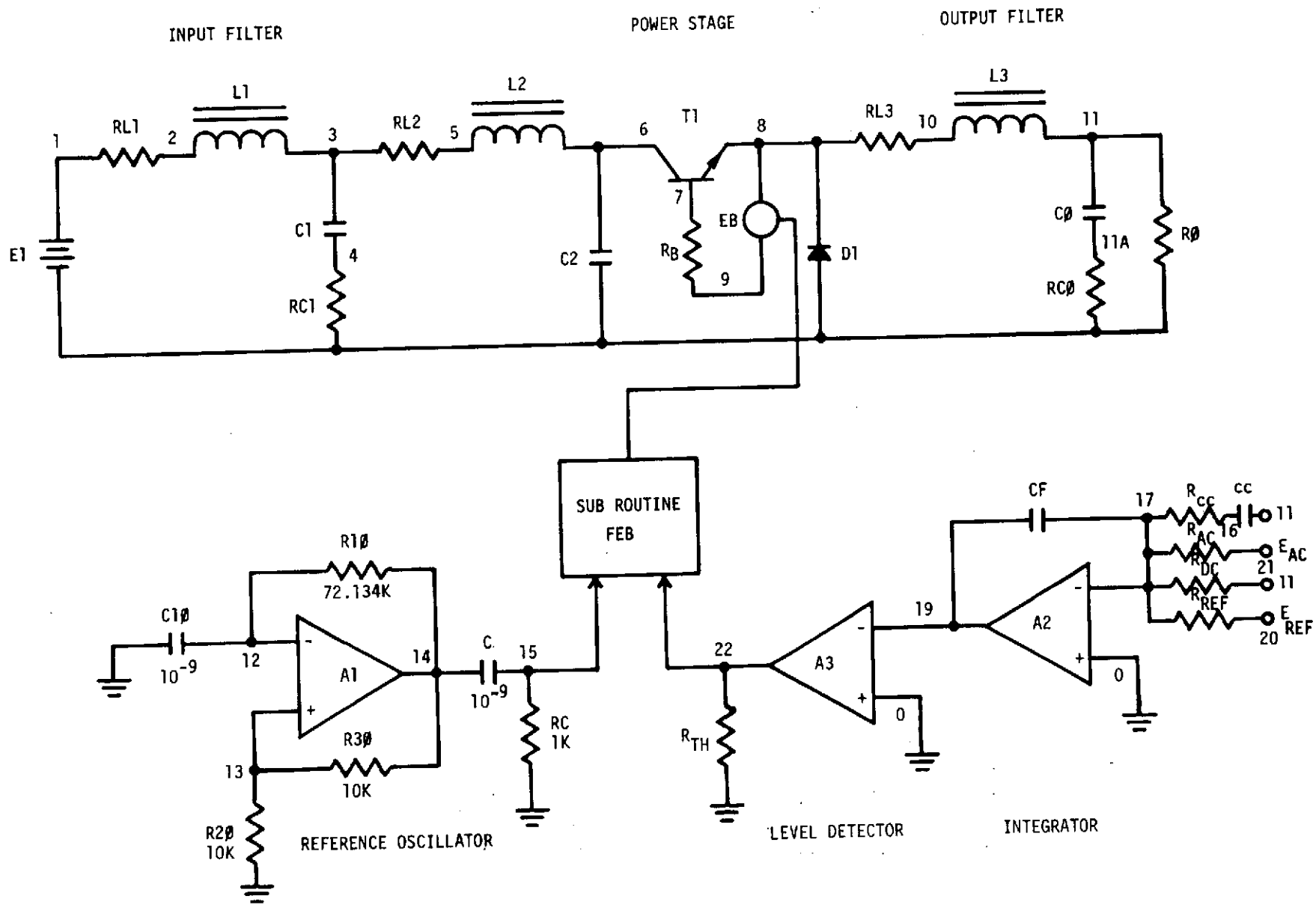


Figure 38.

TIMING DIAGRAM

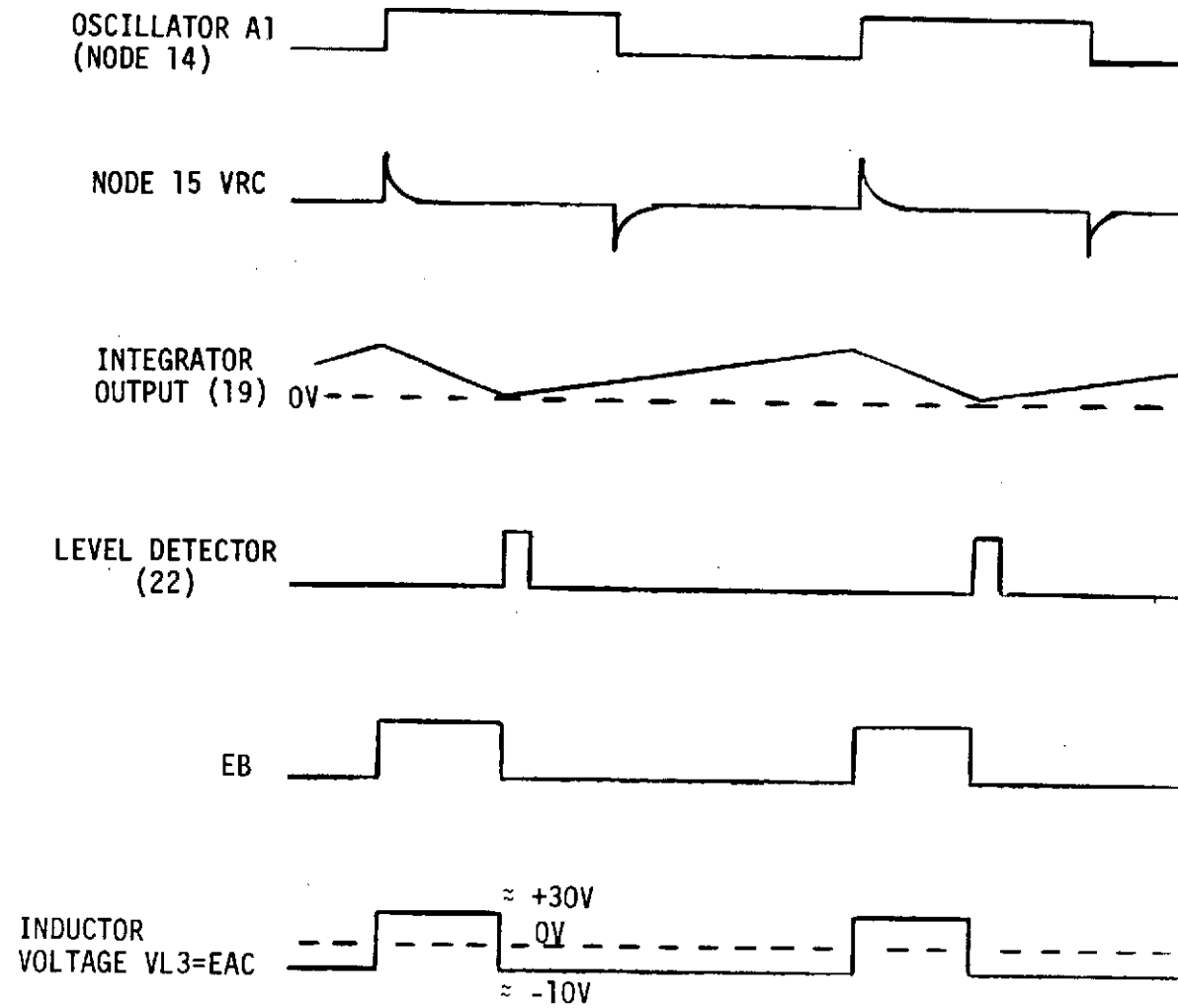
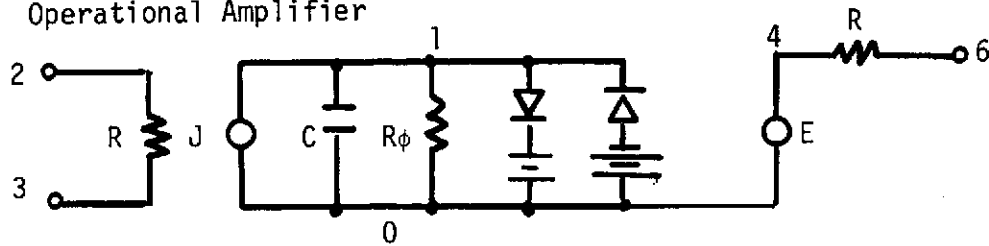


Figure 39

a) Operational Amplifier

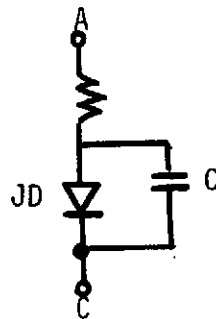


where $J = V_R \times \text{Open Loop Gain} \frac{1}{R_\phi}$

$$E = 1. \times VR_\phi$$

The saturation voltage is controlled by the two diodes and two voltage sources to give approximately $\pm 10V$.

b) Diode Model



The current JD is expressed with the diode equation which has the form:

$$JD = I_s \left[e^{\frac{Q}{KTM} V_{JD}} - 1 \right]$$

where: V_{JD} is the voltage across JD

$$\frac{Q}{KTM} = 38$$

I_s = Saturation Current ($.7 \text{ E-11}$).

The capacitor C is a function of the current J_D to simulate the storage time of the diode

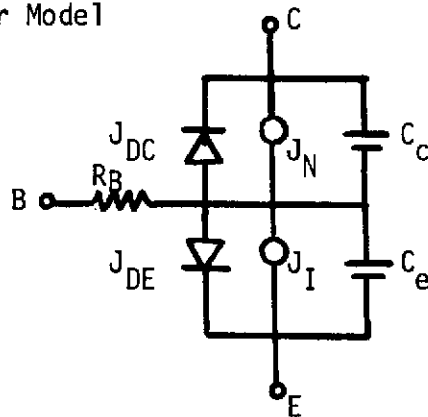
$$C = C_0 + J_D \tau \frac{Q}{KTM}$$

τ = Time Constant

C_0 = Capacitor Value for $J_D = V_{JD} = 0$

C_0 is normally a function of reverse diode voltage but is set to constant for simplicity.

c) Transistor Model



The transistor model used is a simplified Ebers Moll Model. The saturation and cut-off regions are simulated by the two diodes J_{DC} , J_{DE} and the two current sources J_N , J_I .

$$\begin{aligned} J_N &= d_N J_{DE} & d_N &= \frac{\beta_N}{\beta_N + 1} \\ J_I &= d_I J_{DC} & d_I &= \frac{\beta_I}{\beta_I + 1} \end{aligned}$$

β_N and β_I are the normal Beta and inverted Beta, respectively. The capacitors C_e and C_c are treated the same as described in the diode model.

Table 29 illustrates the format of the input data to characterize the series switch buck regulator. Table 29(A) defines the model for the transistor, diode and operational amplifier. Table 29(B) defines the other components for the circuit shown in Figure 38. Table 29(B) and (C) establish the initial conditions in all components. Table 29 (D) defines the subroutine FEB to control the power switch T1 as a function of the signals from the reference oscillator and level detector.

Figures 39, 40, and 41 illustrate the plot of the operational data from the computer run. Figure 39 is the output of integrator A2. Note that the integrator waveform goes through to a negative value. This signifies the effect of the storage time of the power transistor T1. This is an important parameter to simulate in that it effects the line rejection characteristics of the series switch buck regulator.

Figure 40 illustrates the output voltage including the output ripple. Because of the initial conditions specified, the output has not yet reached an equilibrium condition and needs another two switching cycles to complete the transient. The peak to peak output ripple was checked with the design equation (16) of Appendix 11.20, and was found to be the same, thereby proving the mathematical design equation.

Figure 41 illustrates the current in the power diode D1. The diode model included reverse turnoff current and causes the high negative current.

The total computer machine operating time for the example was 7.5 minutes to simulate 300 microseconds of the series switch buck regulator operation.

The different models must be modified to eliminate some of the high frequency parameters that do not effect the output performance characteristics but contribute to some internal switching loss.

During phase II, the model will be revised to include the startup transient, ac input disturbances, ac output disturbances, step input and output disturbances and output fault conditions.

This data will be used to determine interactions between power and control circuitry, to check the mathematical design equation and to aid in developing feedback control loop analysis.

TESS PROGRAM INPUT

```

*
NAME,734300, BACHMANN,M.
MODEL DESCRIPTION
MODEL 2N5154 (B-E-C)
ELEMENTS
RG,B-1=1
CC,1-C=Q1(200.E-12,PTOC,JDC,JI,36.)
CE,1-E=Q1(600.E-12,PTOE,JDE,J4,36.)
JDE,1-E=DIODE EQUATION(.13E-19,36.)
JDC,1-C=DIODE EQUATION(.7E-11,38.)
JN,C-1=Q2(PBN,JDE)
JI,E-1=Q2(PBI,JDC)
DEFINED PARAMETERS
PTOC=20.E-7
PTOE=15.E-7
PBN=100.
PBI=4.
FUNCTIONS
Q1(A,B,C,D,E)=(A+B*(C-D)*E)
Q2(A,B)=(A*B/(A+1.))
MODEL 1NXXXX (A-C)
ELEMENTS
JD,1-C=DIODE EQUATION(.7E-11,38.)
R,A-1=.02
FUNCTIONS
Q1(A,B,C,D)=(A+B*C*D)
MODEL OP (2-3-6-D)
ELEMENTS
R,2-3=1E7
C,1-0=1.59E-7
RO,1-0=1E5
J,1-0=Q1(VR)
EB1,0-7=-9.3
EB2,0-8=9.3
JU1,7-1=DIODE EQUATION (.7E-11,33.)
JD2,1-8=DIODE EQUATION (.7E-11,38.)
RO1,4-6=100
E,0-4=Q1(VRO)
FUNCTIONS
Q1(A)=(1.*A)
CIRCUIT DESCRIPTION
CHOPPER CONVERTER TRANSIENT MODEL

```

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TABLE 29(A)

ELEMENTS
 E1,0-1=40
 RL1,1-2=.05
 L1,2-3=600E-6
 C1,3-4=150E-6
 RC1,4-0=2.5
 RL2,3-5=.03
 L2,5-6=200E-6
 C2,6-0=10E-6
 RSW,6-8=FUNCTION FEB(VRC,VRTH,TIME,EAC)
 DRSW,6-8=1E-9
 D1,0-8=MODEL 1NXXXX
 RL3,8-10=.05
 L3,10-11=200E-6
 CC,11-11A=200E-6
 RCO,11A-3=.06
 RO,11-0=2.5
 EREF,0-20=-10
 RREF,20-17=20E3
 RDC,11-17=20E3
 EAC,0-21=Q1(VL3)
 RAC,21-17=20E3
 CC,11-16=1E-7
 RCC,16-17=1E3
 CF,19-17=1E-8
 A2,17-0-19-0=MODEL OP
 A3,19-0-22-0=MODEL OP(CHANGE C=1.59E-10)
 RTH,22-0=1E4
 CO1,12-0=1E-9
 RO1,14-12=27.4E3
 R20,13-0=1E4
 R30,14-13=1E4
 A1,12-13-14-0=MODEL GP(CHANGE C=1.59E-9)
 C,14-15=1E-10
 RC,15-0=1E4
 OUTPUTS
 VRSW,IRSW
 IC2,EAC
 INITIAL CONDITIONS
 IL3=4.33132
 VC=9.26422
 VCF=3.90795E-1

TABLE 29(B)

VCA2=.440753
VCO=9.94897
IL2=1.02555
VCA3=-9.95055
VCA1=-9.18625
VC2=39.2307
IL1=1.06253
VCO1=4.91130
VCC=10.0062
VC1=39.9042
VRA2=-9.41937E-3
VRTH=-9.85203
VRO=9.95247
VRC=-18.1737
VR20=-4.45006
VRL3=.216566
FUNCTIONS
Q1(A)=(1.0*A)
RUN CONTROLS
STOP TIME=300E-6
COMPUTER TIME LIMIT=15
INTEGRATION ROUTINE=GEAR
MINIMUM STEP SIZE=1E-30
END

```

FUNCTION FEB(VRC,VRTH,TIME)
DATA IFL,XT,XVRC,XVRTH/4*0./
IF(TIME-XT)20,20,10
10 IF(XVRC.GT.18.5) IFL=1
   IF(XVRTH.GT.9.8) IFL=0
20 IF(VRTH.GE.-8.) GO TO 500
   IF(VRC.GE.1.) GO TO 100
   IF(IFL.EQ.1) GO TO 200
   IF(IFL.EQ.0) GO TO 600
100 IF(IFL.EQ.1) GO TO 200
    FEB=VRC-1.
    IF (FEB.GE.5.) FEB=5.
    GO TO 700
200 FEB=5.
    GO TO 700
500 IF(IFL.EQ.0) GO TO 600
    FEB=5.-(VRTH+8.)
    IF (FEB.LE.0.) FEB=0.
    GO TO 700
600 FEB=0.
    GO TO 700
700 CONTINUE
    XVRTH=VRTH
    XVRC=VRC
    XT=TIME
    RETURN
END

```

TABLE 29(D)

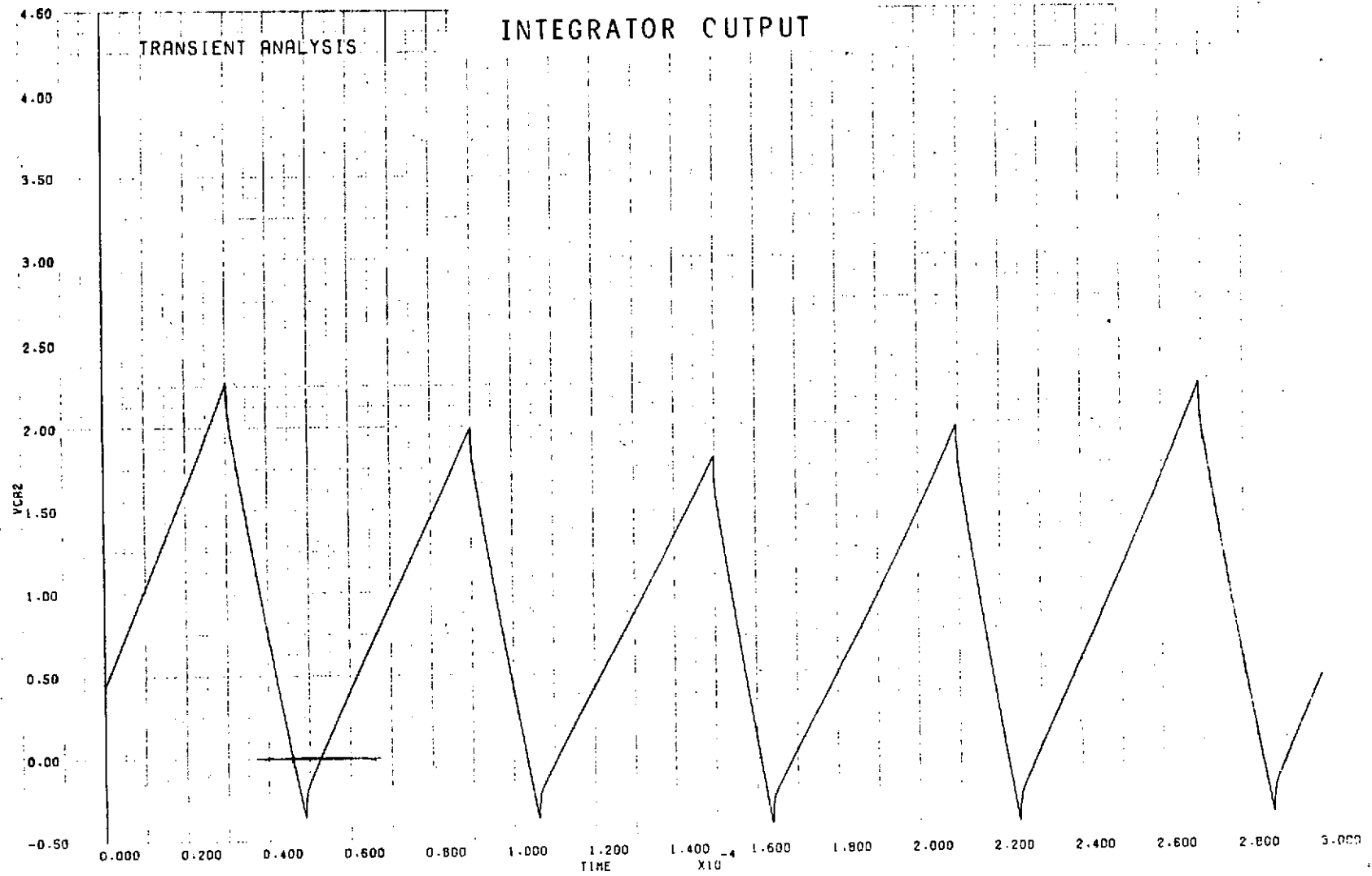


Figure 39

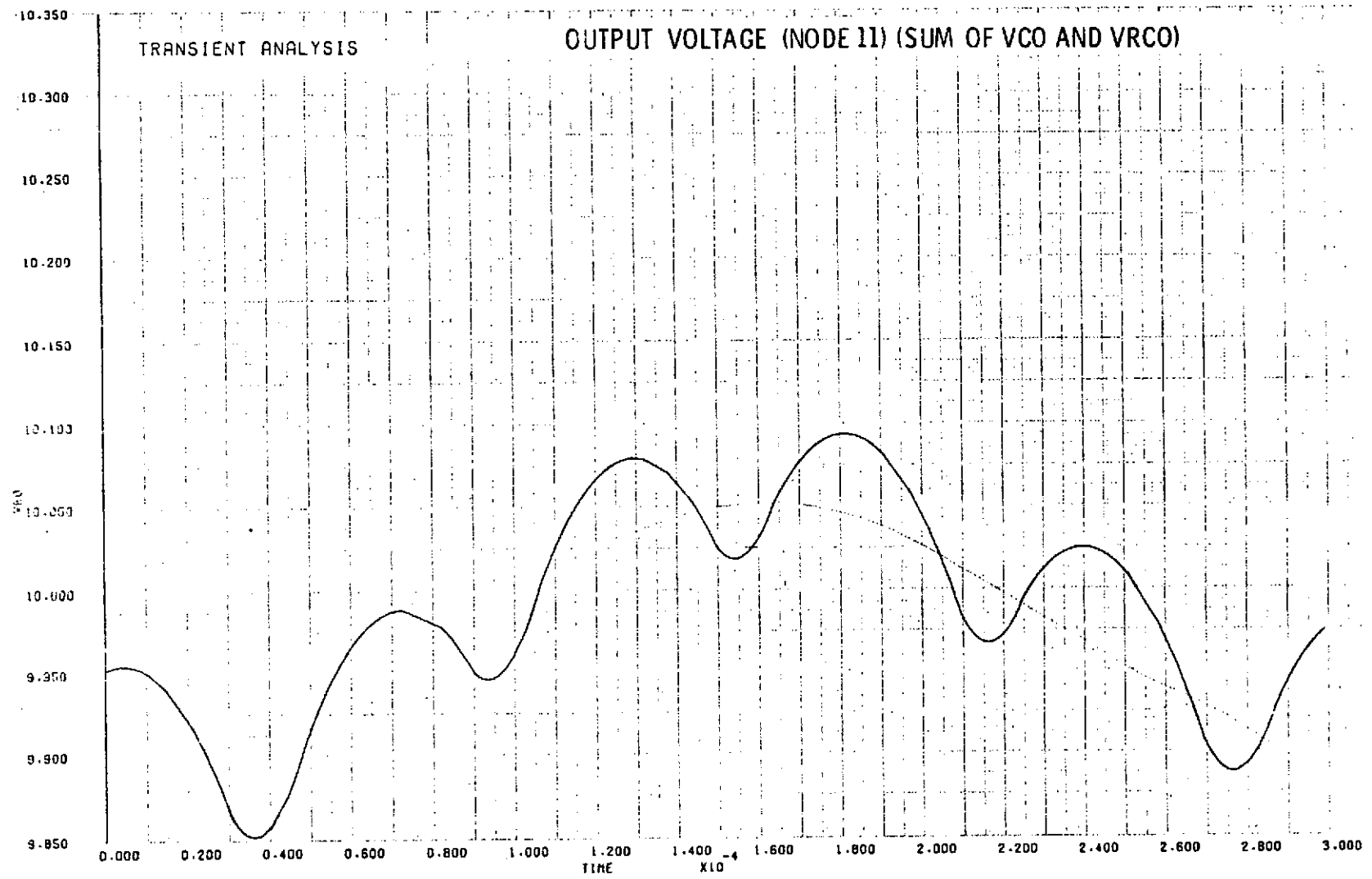


Figure 40

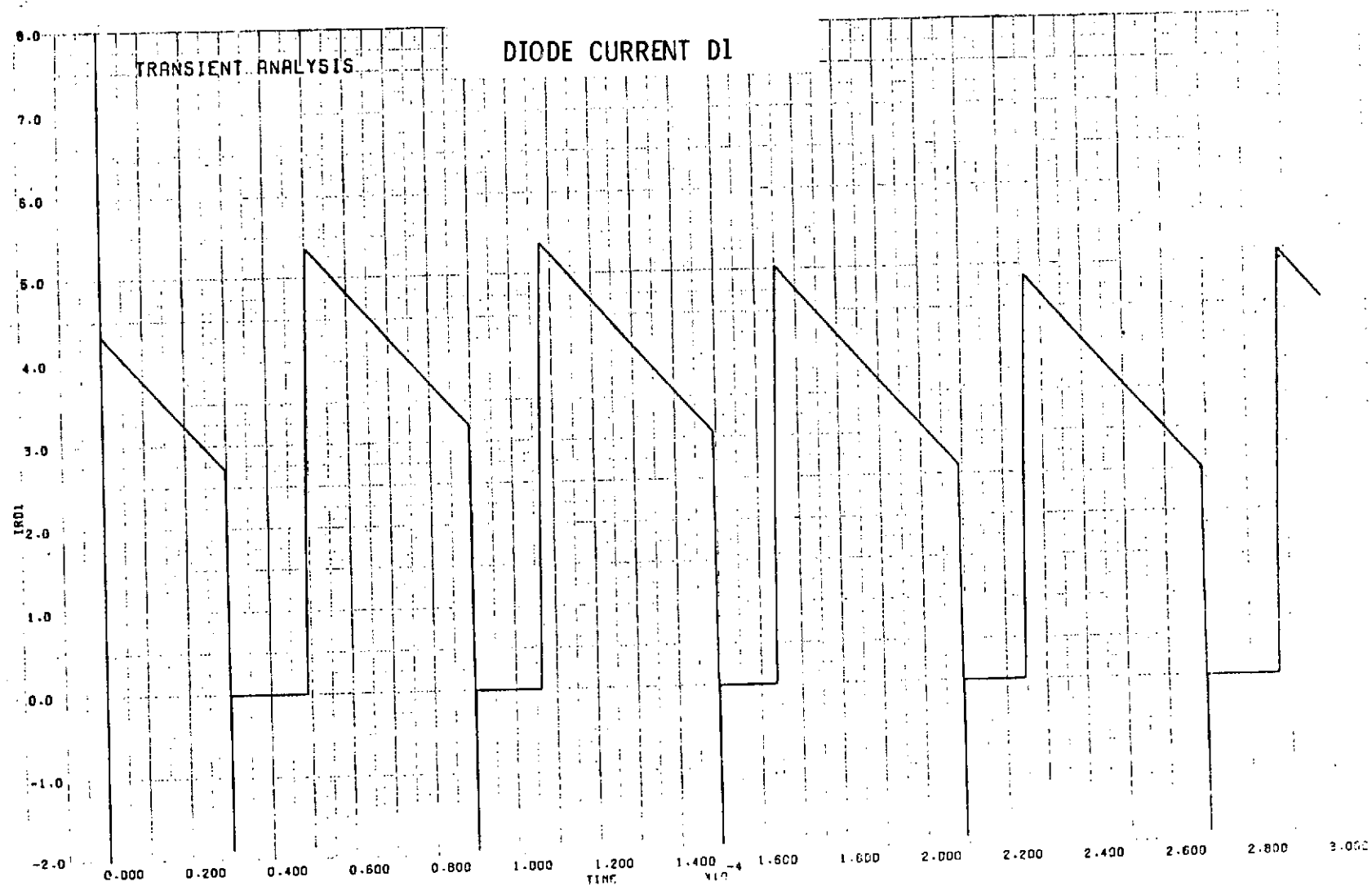


Figure 41

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